
Pavement
Management Systems

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MODULE 1

AN INTRODUCTION TO ASSET MANAGEMENT SYSTEMS

1.1 Instructional Objectives

This module introduces the fundamental principles of an asset management system that are common to agencies managing integrated infrastructures and other industries (e.g., trucking and rail). The applicability of these principles to pavement management will be presented through a systems approach. Upon completion of this module, the participant will be able to accomplish the following:

a. Identify the fundamental principles involved in asset management.
b. Understand the philosophy of asset management.
c. Describe the issues affecting the success of asset management today and in the future.
d. Understand the applicability of asset management concepts to other highway issues.

Over the years, private industry has implemented management systems to provide quantitative and qualitative information about the agency's resources and the facility's current and future performance levels *(2)*. These systems, referred to as an Asset Management System (AMS) or commonly as an Infrastructure Management System (IMS) are being used to manage network inventories that include parking lots, buildings, transit facilities, waterways, and utilities.

DEFINITION OF ASSET MANAGEMENT SYSTEMS (AMS): Although there is no one universally accepted definition of an AMS, these systems provide the tools that are necessary fo the monitoring and preservation of a facility's assets on a continuous basis to ensure the efficient and effective use of the agency's available and projected resources. More specifically, asset management can be defined in the following way *(2)*:

> Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively.

Through the combination of sound engineering principles, accepted business practices, and economic theory, AMS provide the tools necessary to improve the decision-making process by providing timely information in an organized, logical, and justifiable manner. As a result, an agency using Asset Management can improve the effectiveness of its short-term decisions through an analysis of long-term impacts.

COMPONENTS OF AN ASSET MANAGEMENT SYSTEM: In order for an AMS to effectively assist an agency with the management of its assets and other resources, a system must be tailored to match the resources and needs available. The framework of a system, however, is fairly consistent and should be comprised of the following elements.

- An inventory of assets
- A method of assessing current condition or performance
- A process for determining needs
- Tools to evaluate and select appropriate strategies to address the needs
- Methods to evaluate the effectiveness of each strategy

Consequently, an AMS generally contains the following:

- A centralized database for storing and retrieving inventory information
- Performance prediction models that permit the projection of future asset conditions
- Analysis tools that are customizeable to match the policies and procedures used by the agency to identify and prioritize maintenance and rehabilitation needs
- Reporting tools that provide a variety of informative reports, including detailed reports, summary reports, and graphics

These elements are identical to the components of a pavement or bridge management system; the variations occur in the types of assets being managed, the models used to analyze the conditions, and the approaches used to determine needs.

Goals and Objectives of Asset Management: In both public and private agencies, one of the primary functions of a management system is to assist the agency with its decision-making through processes designed to improve the flow of information and assist in evaluating current and projected preservation strategies. Unfortunately, improvements in decision-making are very difficult to identify and quantify, so agencies frequently find it difficult to demonstrate the effectiveness of these systems. Improvements in transportation system performance or improved profitability for a private agency are more demonstratable measures of the success of these systems than the nebulous improvements in decision making or improved communication of data.

Because of the difficulty in measuring the effectiveness of an AMS, many agencies have identified goals for their management systems that specifically include items whose improvement can be quantified. Additional benefits provided by the system, while not specifically stated as goals, are gained through the effective use of the management system but are not frequently documented through case studies.

In order to achieve the goals set out by the agency, specific objectives must be stated that provide a means of achieving the goals. In general, the objectives should be measurable although that is not always possible. The objectives stated by private industry are perhaps more clearly quantifiable than those of governmental agencies due to their need to remain competitive and profitable and their detachment from many political and governmental constraints. A recent seminar on asset management identified the following quantifiable objectives from an AMS *(2)*.

- Enhanced knowledge of inventory and asset value
- Development of links that tie resource allocations to savings from replacement
- Establishment of standardized processes and protocols
- Consideration of life-cycle costing in the decision process

The same reference *(2)* also identified several agency objectives that would be difficult to quantify. These include the following items.

- Recognition of data as a *corporate asset*
- Creation of a sense of ownership in assets by corporate managers and operators
- Improved credibility in decisionmaking
- Encouragement in processes that have managers *think globally, but act locally*
- Improvements in teamwork, communication, and training

Overall, these objectives are designed to achieve the overall goal of providing the decision-makers access to the data they need to more efficiently and effectively manage the facility's current and future performance. As can be seen by a review of the objectives listed above, the attainment of this goal requires the coordinated application of a variety of technical principles, including engineering, planning, economics, and budgeting. It also requires the involvement of individuals from all levels of the organization, such as equipment operators, foremen, managers, owners, and stockholders. For governmental organizations, it also requires buy-in from individuals in a number of different divisions, such as maintenance, planning, and research. It is this cooperative involvement that sets an effective implementation apart from a less effective one.

Benefits To Using an Asset Management System: Corporations practicing asset management report that the systematic approach to managing its facilities is necessary to stay competitive in today's environment. As a result, the use of these systems is viewed as a necessity rather than an optional activity; largely because of the benefits gained by the organization. Some of the benefits realized by these organizations are listed below (2*)*. In general, these benefits provide improvements to the type and flow of information used in the decisionmaking process or effect the productivity and cost-effectiveness of the organization.

- Improvements to program quality
- Improved information and access to the information
- Facilitates the economic assessment of various tradeoffs
- Provides improved documentation of decisions
- Provides improved information on return on investment and value of investments
- Reduces both short- and long-term costs

Regardless of the type of agency using the management system, it will be most successful in obtaining benefits if the following attributes are addressed through the system *(2)*.

- It establishes a common understanding of performance measures and criteria
- It provides understandable results in a user-friendly environment
- It is customer-focused and mission-driven
- It is accessible at many levels within the organization
- It is flexible enough to be able to accommodate change within and outside the organization
- It is linked to the technical analysis, decisionmaking, and budgetary processes
- It facilitates the education of users and decision-makers

Consequences of Poor Asset Management: As discussed in the previous section, it is often difficult to document the benefits derived from the implementation of an AMS. It is less difficult to find examples of agencies and assets that could have been better managed if a structured decisionmaking process had been in place. One of the most obvious examples is the collapse of the Silver River Bridge on December 15, 1967 during rush hour traffic *(11)*. Based on varying reports from witnesses, the entire bridge collapse occurred within less than 30 seconds resulting in 46 deaths and 9 injuries. Around this time period, a number of bridges across the nation also failed, prompting Congress to madate a National Bridge Inventory (NBI) to identify the structural and functional adequacy of all bridges on the nation's highways; information not previously collected. Using the inventory information, several states began the development and implementation of bridge management systems.

There are other examples as cited in Ref. *(11)*. The Miami-Dade Water Sewer Department in Dade County, Florida provide an excellent example of a public works agency that suffered due to the lack of information. In 1973, a metropolitan water and sewer agency was established for the area. The agency was comprised of about 30 smaller systems and received federal money to bring all of the systems into compliance with existing standards. Instead, the Department used the funds for capital expansion projects enabling them to retain low water and sewage rates for the public. As a result of this decision, maintenance activities were inadequately funded, leading to infiltration and inflow. The outdated designs used in the systems led to widespread cavitation. In the late 1980s, this eventually led to system-wide deterioration, culminating in the collapse of a sewer pipe under the Miami River in 1992. The collapse, combined with the frequent overflows caused by the infiltration and inflow, caused raw sewage to spill onto roadways and into the Miami River and other bodies of water.

A similar event took place in Chicago, Illinois on April 13, 1992 when a freight tunnel running under the Chicago River ruptured, causing 250 million gallons of water into the tunnel system. Over 400 businesses flooded, causing many of them to shut down for a week or more, resulting in damage estimates of over $1 billion dollars. In this instance, city information provided to a company pounding piles near the tunnel showed no record of any tunnels in the area. The city engineer in charge of monitoring the piling job never made a final inspection, which could have alerted the city to the problem prior to the collapse, because he was unable find a parking place close to the site.

Transportation systems are also affected by poor asset management. The deterioration of a road network frequently leads to a lower level of comfort for passengers, possibly a lower rate of acceptable traveling speed, and increased operating expenses for vehicles traveling on the road system. Further, these factors influence the efficiency and cost-effectiveness of other industries such as shipping companies or other transport agencies.

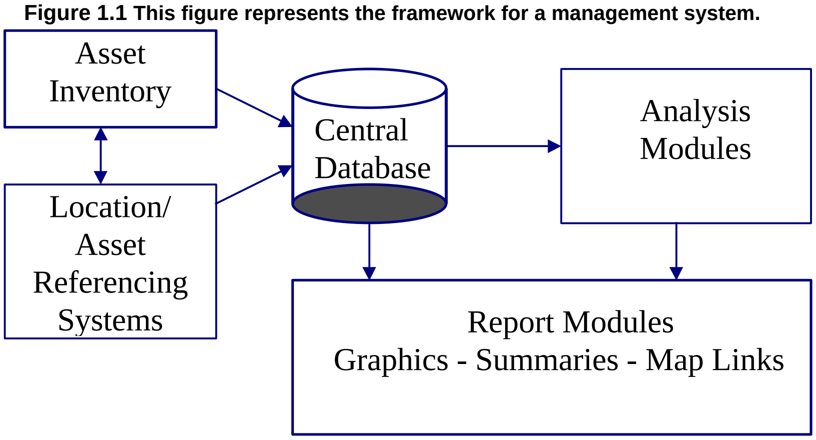
The number of examples of poor asset management is overwhelming. It is interesting to note, however, that each of the examples presented in this section could have ended much differently had an effective AMS been in place.

1.3 Framework for Asset Management

Asset management involves the development and implementation of structured processes to improve the decision-making capability of an agency. Without question, processes and procedures can be developed to manage any type of asset independently, or a group of assets making up a facility. The types of assets being managed, the organization using the system, and the resources available all have a tremendous influence on the level of sophistication of the system and the types of models used to assist in the decision-making process.

Although the AMS will vary due to the factors discussed previously, a framework for the system can be described. Agencies have found the most success with systems that are developed with modularity in mind so that modules of the system can be updated and replaced as technology changes or if other factors influence that portion of the system. Figure 2.1 presents a simplified representation of the framework.

Figure 1.1 This figure represents the framework for a management system.



A brief overview of each of the major components is provided in the following sections.

Asset Inventory System: In order to manage a group of assets, it is imperative that the agency know which assets are included and conduct an inventory of the basic characteristics of the assets. It is also critical that the condition of the assets be recorded through an objective rating system and the age of the asset be estimated as closely as possible.

Location/Asset Referencing Systems: In order to manage the assets of an organization, it is imperative that the location of each asset be identified. In a transportation agency, this means the development of a location referencing system that ties segments of the facility to a geographical location. In a private-sector industry, this could mean establishing the location of many geographically separated parking lots, establishing referencing systems for buildings, or setting identifiers for equipment.

Central Database: Information about the assets is stored in a central database that provides access throughout the organization. To be most effective, the database should centralize the storage of asset information and facilitate the handling of data in an efficient manner. A centralized database eliminates the need for the maintenance of separate databases for different types of information although databases that extract information from the central database for analysis may be useful.

Analysis Modules: One of the most important functions of a management system is the ability to analyze data so that various scenarios can be evaluated and effective short- and long-term decisions can be made. To facilitate that analysis, modules must be developed that can forecast future asset conditions and conduct multi-year analysis to compare the impacts of various scenarios. The analysis should include modules that effectively allocate resources to different types of expenditures, such as maintenance and rehabilitation in a transportation agency. Agencies with a number of different types of assets, such as a city managing several infrastructure components, may also require modules that compare and contrast expenditures on one type of asset over another.

Reporting Modules: The information contained in the database, and the results of the analysis, are only useful if the information can be conveyed to the user in a user-friendly format that matches the users needs. Today, management systems make use of graphical reporting features that convey important information in a manner that can be assimilated quickly.

Some agencies have linked their management systems to geographical information systems (GIS) that visually display information on agency maps. These systems are very useful for linking and displaying different types of information.

1.4 Issues in Asset Management

In order to remain competitive in industry today, private-sector agencies find that the use of asset management systems is imperative. Many highway agencies, although interested in the capabilities of management systems, find that the full capabilities of these systems are not being fully utilized for a number of reasons. Some of the reasons given for a highway agency not using the capabilities of a management system include the following *(10).*

- The presence of a management philosophy that adheres to a worst-first policy
- Outside influences that strongly influence the allocation of resources
- A tremendous backlog of needs that the agency wants to address before considering more cost-effective solutions that may place a heavy emphasis on maintaining assets in good condition

In some highway agencies, management systems are not successful due to a lack of cooperation and coordination between system users. As a result, agencies may find a number of separate databases being maintained, with several common data elements which could have been shared. This leads to duplication of effort, the potential for different data being used by different divisions, and often leads to differing referencing systems for identifying assets.

Even highway agencies that have been successful in implementing the philosophy of asset management within their organizations face challenges in order to keep the systems current and the data relevant to existing conditions. For these reasons, it is imperative that each agency develop a process for periodically reviewing the models used by the management system for identifying and recommending actions, incorporating new technology, and measuring the effectiveness of the system. Areas found to be ineffective or non-representative should be replaced with more appropriate models. This is most easily accomplished with modular systems that do not require the entire system to be replaced as modifications are required.

Hurdles to Asset Management: In addition to the technical and agency issues that have already been discussed, there are a number of challenges that both private- and public-sector agencies must consider carefully while planning the implementation of an AMS. These hurdles entail a number of different areas, such as those listed below.

- Technical hurdles
- Institutional (agency) hurdles
- Implementation hurdles

Each of the different types of hurdles will be introduced and discussed briefly in the following sections.

Technical Hurdles: In previous sections of this module, the importance of designing a management system to match the decision making process within the organization has been emphasized. This affects the success of the implementation in a number of ways. First, the system must be able to match the needs of the various system users by providing the types of information each user needs in a format that matches the level of detail required. This factor influences the level of sophistication of the system and the models used to assess conditions, forecast future conditions, identify needs, and produce optimized programs for various budget scenarios.

The system must also be flexible enough to accommodate changes; both changes in technology and changes in practices and procedures. These changes must be incorporated without rendering the entire system unusable, once again emphasizing the importance of a modular development.

It is also imperative that the agency develop processes that permit the evaluation of system effectiveness through feedback loops that compare actual practices to the system models. These processes could be used to compare the actual service of life of a particular asset to the performance models incorporated into the management system. If the feedback loops demonstrate that any of the models are inaccurate or in need of updating, the appropriate changes should be made in order to provide an acceptable level of effectiveness in the recommendations.

Institutional (Agency) Hurdles: A technically sophisticated management system can only be effective within an organization that gives credance to the recommendations from the management system. This requires that the agency support the development, implementation, and on-going support of the management system from top-level management throughout the entire organization. It is difficult to maintain this level of support from top management without demonstrating the success of the system to help the agency better manage its assets through increased profits or higher levels of asset conditions. This is especially difficult in the public sector where agencies are often heavily influenced by political appointees and elected officials who place more weight on short-term solutions than long-term objectives.

In several agencies, pavement management development efforts suffered because of the lack of coordinations between individual users of the pavement mangement system. This lack of coordination between functions becomes even greater within agencies responsible for the management of a number of assets previously managed using separate tools. For example, pavements may have been managed using a pavement management system, bridges managed using a bridge management system, and signs managed with yet another system. Undoubtedly, each system required a full inventory, condition assessment, database, and analysis tools.

Today's management systems are capable of managing each of these different infrastructure components through a more comprehensive and coordinated systemic process. This requires that individuals from throughout the organization participate together in system development meetings to ensure a more integrated approach to managing the agency's entire system. This may require some fundamental differences in the way many agencies manage their assets, especially in the public sector. In the past, turf battles often kept different types of information separated. Today, that practice must change.

Implementation Issues: It is important for agencies using management systems to realize that even after the system has been designed and implemented, there are on-going efforts that are required. One requirement is continual support in terms of resources to continue to collect the information needed to maintain the system, update the models, and take into account new technological changes. If any one of these aspects is ignored, it will not take long before the information from the system is outdated and the confidence in the system recommendations destroyed.

It is also important that individuals working with the management system receive opportunities for training and technology transfer through conferences, classes, workshops, and other means. Participation with other agencies using management systems is extremely beneficial for the exchange of information dealing with implementation issues and/or uses of data. The Executive Seminar on Asset Management sponsored by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) in September 1996 is an excellent example of such an exchange of technology.

Future Issues: Over the past twenty years, there has been tremendous progress in the development of management tools to assist agencies make more cost-effective decisions based on quality data. Even so, there are a number of areas to address in the future to continue to enhance the capabilities available today.

From a global view, there is still a great deal of effort that can go into the development of strategic investment analysis tools. In the public sector, there are few working examples of management systems that provide for the comparison of investing in one asset over another or investing in maintenance strategies over capital expenditures. As these systems become developed and tested, this area will undoubtedly receive a great deal of attention.

There is also a great deal of training that is still required among upper management, politicians, and the public. While most people understand the importance of periodic maintenance to keep up the value and operation of a car, it is surprising that few apply that same paradigm to our roads or our pipelines. Those individuals involved in asset management must continue to promote the benefits as political terms end and new management is brought on board.

As this training takes place, there will be a gradual shift in the way organizations manage their assets. Over time, agencies will focus more on the overall performance of their assets and the return on investment from different investment strategies. Consequently, these agencies will focus more on the best use of its assets as a whole, rather than the management of assets as individual and separate pieces of the organization.

This broader outlook will have a tremendous impact on the individuals providing information to management. Historically, management systems have been operated by individuals with training or experience in the engineering and other technical fields. With time, the skills required to operate these systems will require training in other fields, such as business, economics, and multiple-criteria decision making techniques (such as multi-variate analysis).

Other changes can also be expected as technology changes and the philosophy behind management systems becomes more accepted. These changes are expected to influence the way we work, the type of work we perform, and the basis for making the decisions we make.

1.5 Applications of Asset Management to Transportation Systems

For over twenty years, transportation agencies have been developing and implementing management systems to help engineers, planners, and managers make more informed, cost-effective decisions about the infrastructure components for which they are responsible. For the most part, these efforts have involved pavement and bridge management systems, although integrated infrastructure management systems have also been developed in recent years.

To some degree, the need for transporation management systems arose out of concern about the condition of infrastructure components. National studies on infrastructure needs summarized the investments in the infrastructure that would be required in order to maintain minimal condition levels *(1)*. The Federal Highway Administration (FHWA) summarized the condition of the nation’s highways and bridges in a study conducted in 1989. This study reported that 11% of the interstate highways were in unsatisfactory condition, 15.9% of interstate highway bridges were deficient, and an average annual investment of $25 billion was required between the years 1987 and 2005 just to maintain 1985 condition levels. Today, these estimates severely underestimate the growing funding requirements needed in the transportation area.

As a result of these studies, government agencies sought out methods to improve the objectivity of their decision-making processes through systematic means of determining existing conditions, identifying needs, and prioritizing the needs using multi-year analysis techniques that reported the impacts of the decisions on future conditions. Through the use of these methods, agency personnel were better able to respond to fiscal constraints placed on agency resources.

Concepts of Asset Management Systems for Transportation

The concepts of asset management are very similar to the concepts used by transportation agencies in pavement management and infrastructure management systems . Many of the components and procedures used in asset management are directly applicable to a transportation system, as shown in the list below *(1)*.

- The assets must be inventoried
- An objective form of condition measure must be applied to determine existing conditions
- Performance measures must be applied and future measures of performance must be estimated
- An integrated database that maintains data quality and enhances data access must be available
- The system is optimized as a whole rather than merely the optimization of each individual project
- The selection of strategies requires an iterative process that considers life-cycle costs and not just initial costs
- Outputs must be in a useful format and must be readily available

These systems require a sound understanding of the inputs to the system, the way the information is optimized, and any constraints that may limit the application of the models. They depend on models that represent the behavior of the system and the conditions under which maintenance and/or rehabilitation will be applied.

A number of approaches have been proposed for the broader application of these principles to transportation agencies. One such approach *(8)*, views a comprehensive highway management system as a three-dimensional matrix, as shown in Figure 1-2. The three dimensions represented by the system include the highway facilities, the operational functions, and the overall system objectives. These dimensions are further explained in Table 1-1.

This framework views the management of the highway as a multi-criteria decision process in which each facility is managed in order to achieve overall system objectives. It demonstrates the coordination and interaction issues that must be addressed for this type of system to be used effectively.

Figure 1-2 Three-dimensional matrix structure of a highway management system *(8)*

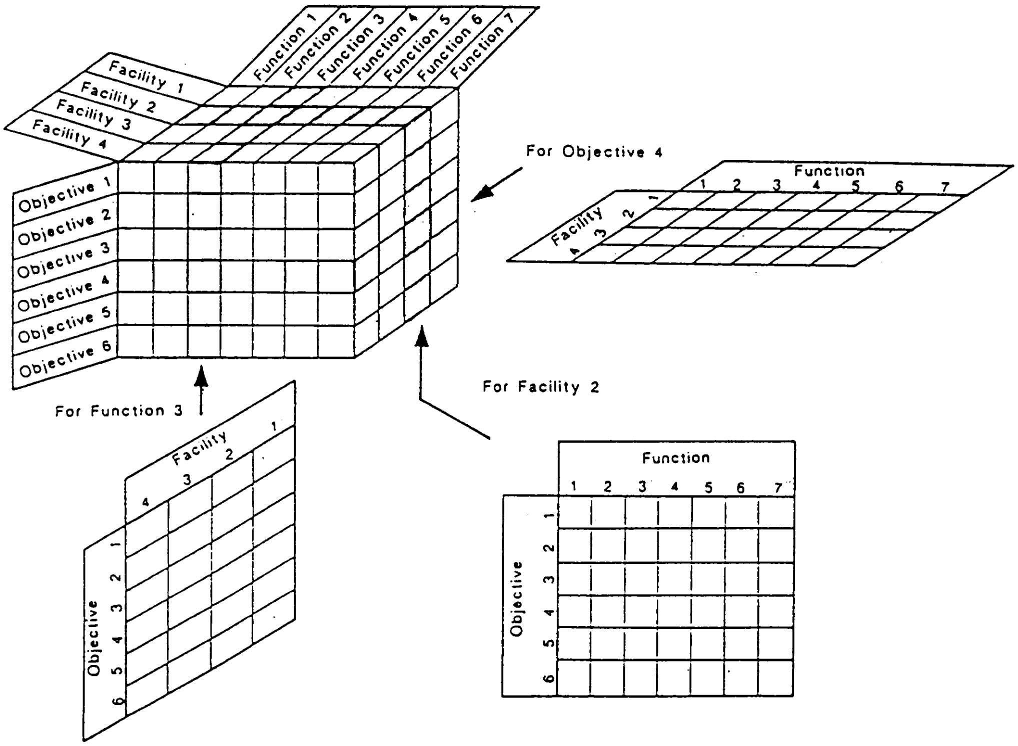


Table 1-1.

Highway Facility	Operational Function	System Objective
Pavement	Planning	Service
Bridge	Design	Condition
Roadside	Construction	Safety
Traffic Control Device	Condition Evaluation	Cost
	Maintenance	Socioeconomic Factor
	Improvement	Energy
		Data Management

Inherent in the application of these principles to the highway network is the inclusion of risk management principles. These principles permit the agency to consider the probability that each factor used in the analysis will exist as assumed, so that the agency can evaluate the likelihood of system optimization under varying conditions. Risk analysis provides the agency with an overall sense of the risk involved in following the recommended actions.

Systems Approach and Its Application To Pavements: Throughout the remainder of this course, the participants will focus on the application of these principles to pavement management. In reality, there are many similarities to the approaches being used in asset management with those that have been used for many years in the pavement management field. Both require the use of a systematic process to perform the following tasks *(3)*.

- Identifying the key links between one or more strategies, where investment in one strategy (such as preventive maintenance) affects another (such as reconstruction)
- Defining the various strategies for improving the effectiveness of these interactions
- Evaluating and implementing the strategies to enhance the overall performance of the transportation system

The systems model is further developed in the literature *(7)*. The authors in Ref. *(7)* describe a process that involves defining the system elements and boundaries as well as the agency goals and objectives. Once these elements have been defined, the agency develops the system models and outlines an analysis procedure that the system will follow. The final step involves the development of output formats that can be used to convey the information contained in the system to the users in a timely fashion.

The systematic process for pavement mangement is well documented and successfully used in a number of organizations, as will be demonstrated throughout this course. The approach requires a change in the agency's traditional way of thinking by taking into account the availability of useful information, the ability to forecast future conditions, and the results of an economic analysis.

Benefits Realized by Highway Agencies Using Asset Management Concepts: Agencies successfully utilizing structured management systems claim to have benefitted from the use of standardized processes for decision making. When asked to identify the benefits that their agencies have realized through the implementation of a pavement management system, state highway agency personnel provided the following information *(9).*

- A systematic process that operates within the practices, policies, and constraints of the agency
- The ability to forecast future needs
- A better understanding of the impacts of project timing or treatment selection on the long-term condition of the network

These types of benefits can be generally classified as the results of improvements made to the decision-making process through improved access to information about the facility. There are other types of benefits that may be realized, such as improvements to the productivity of an agency. For example, private-sector agencies have reported improvements to the delivery of client services from some point in the future (say 2 days) to real time delivery *(1).*

In order to realize these benefits, the agency using the management system must realize that a management system must fit within the agency in order to be useful. It is imperative that the agency's culture be conducive to, and accepting of, the information available. The following factors should be considered to derive the greatest benefit from a management system *(10)*.

- Management should understand the philosophy behind the system recommendations as well as the constraints with which it operates
- The system recommendations should reflect the projects that provide the most benefit to the agency, assuming normal conditions are met. There are, however, no guarantees of this benefit
- Different strategies can be developed to match different goals. For that reason, the agency should clearly identify the goal that it is trying to meet
- Management systems provide tools to assist the agency; they are not meant to be a replacement for the experience and expertise of agency staff

1.6 Examples of Agencies Using Asset Management Systems

In order to demonstrate the application of AMS to transportation agencies, several examples of integrated systems from both the private- and public-sector are provided. These examples demonstrate the principles of asset management and the broad application of these principles to achieve an overall agency objective.

Use of Asset Management: Because of the diversity in agencies with assets to manage, there are an almost unlimited number of ways that AMS can be implemented. Private-sector agencies focus their objectives on methods that directly impact the ability of the organization to make a profit. Any areas that do not contribute to the profitability of the organization over time are usually sold or closed. Public-sector agencies do not focus on profitability, but may focus more on the most cost-effective use of available funding and the overall service level provided to the end user. Two examples are provided of agencies using asset management to improved the effectiveness of their organizations; one example is from the private-sector and the other is from the public-sector *(2).*

GTE's Use of Asset Management in the Telecommunications Industry: Due to the changes brought on by deregulation, the telecommunications industry has seen tremendous changes in the competitiveness of the industry. Consequently, GTE has seen its focus shift from efforts to meet regulatory requirements to improved customer satisfaction. GTE uses its asset amangement system to provide the following functions:

- Network management and inventory, including what, where, use, and condition
- Provisioning - providing and configuring equipment to provide needed services
- Planning and engineering, including growth and replacement
- Financial recordkeeping

During the Executive Seminar on Asset Management, a representative from GTE drew parallels between the telecommunications industry and the transportation industry that are relevant to asset management. These include the following points (McNeil 1996).

- Both sectors depend on a public network that is owned and operated jointly by several independent companies. Individual organizations are responsible for their own assets but close coordination is required
- There are hundreds of thousands of network pieces that have to be managed. This includes maintaining information on what they have, what its condition is, and how they will plan for future capacity expansion
- The economic value of the assets is large, representing a large fixed base
- A large investment is required each year to maintain and expand the assets
- The assets are geographically dispersed

GTE stressed that future issues in asset management will continue to focus on the transition from information that was needed in the past to new forms of information needed in the new competitive environment.

Asset Management in the Port Authority of New York and New Jersey: The Port Authority of New York and New Jersey is a quasi-government organization formed over 75 years ago with an annual budget of $2.6 billion, with a quarter of that devoted to capital expenditures. Because of its quasi-government role, the Port Authority has the ability to reinvest its revenues into its facilities, which has been beneficial considering fiscal constraints imposed by changes in State and local governments and the business sector. Each major entity of the Port Authority manages its assets independently.

The Port Authority faces a number of challenges that directly relate to its asset management practices. These include the following:

- An increased emphasis on cost control
- Continued trends to divest, outsource, and privatize
- Increased emphasis on delivering immediately visible improvements in customer service
- Increased antipathy to long-term planning
- Increased expectations on the part of elected officials and political appointees that financial, business, political, and environmental conflicts will be resoloved

The Port Authority sees the structured decision-making process made possible through the use of an AMS as the means to better services to its users, more business opportunities, and a streamlined agency.

1.7 What is Pavement Management?

Pavement management has been defined in various reports and books. *In general, pavement management practices are based on the concept of finding a cost-effective combination of treatments to apply at any given time to give the desired level of service.* Pavement management systems (PMS) that can evaluate various strategies use the expected impact of maintenance and rehabilitation treatments on the future performance of the road surface to:

§ Identify those that need treatment.

§ Identify the mixture of preventive maintenance and rehabilitation actions that will provide the desired overall condition within imposed constraints.

A PMS or road surface management system is a decision support tool that is designed to be used to help make cost-effective decisions concerning the maintenance and rehabilitation of pavements and road surfaces *(13,14,15,16).* Many refer to a set of software programs as pavement management. This is really a misnomer, since the software does not manage or make decisions. The personnel in the organization manage pavements and make decisions; the software only assists in information management and decision support.

Pavement management systems provide a means to organize the massive amount of data that develops with a road and street network. When the data storage and analyses are automated, a PMS stores data, retrieves data, and makes multiple complex calculations quickly and efficiently.

Pavement management has been used to describe management of highway, road and street networks with paved surfaces while road and street surface management, or just road surface management, has been used to describe management of road and street networks with both paved and unpaved surfaces *(17).* Most principles are the same for both systems. However, the unpaved surfaces use more of a work management system without much prediction of condition and less consideration of treatment impact on condition.

In the broadest sense, pavement management covers all phases of pavement planning, programming, analysis, design, construction, and research *(18).* As implemented in most agencies, PMS have been developed to primarily address maintenance, rehabilitation, reconstruction, and, sometimes, new design. They are generally restricted to looking at the maintenance and rehabilitation needs of the existing pavement system and very seldom consider the need for additional pavement area to address increased traffic capacity. Increased capacity needs are normally addressed in congestion management or other planning activities. Other management systems may also identify the need for new pavements or pavement maintenance and rehabilitation needs.

Maintenance addressed in pavement management is primarily programmed or planned maintenance such as surface seals and crack seals. Pavement management systems do not try to predict where a pothole will appear nor the frequency of routine maintenance activities such as pothole filling, temporary repairs, etc. Maintenance management systems should interface with the pavement management systems. Maintenance management systems normally address maintenance work requirements and standards for selected maintenance treatments. The planning for the need of programmed maintenance normally comes from the pavement management or road surface management system.

1.8 Need for Pavement Management

There are over 6 million km (almost 4 million miles) of highways, roads and streets in the United States *(12)*. For many years, highway agencies have used various methods to manage the funding of highway needs within their jurisdiction. New construction of new roads were probably the best managed with planning groups being developed in larger agencies to address where new highways would be built and to determine which should be funded.

Maintenance and rehabilitation generally were managed with less formal methods. In several cases, crises management developed, especially in smaller agencies, as the standard method to address maintenance needs when funds were short. Within the last 20 to 30 years, pavement management systems have been developed to help plan maintenance and rehabilitation of pavements *(18)*. Management systems are necessary to avoid crisis reaction in public works *(19)*. They are the application of systems engineering and basic management concepts to managing our infrastructure. It provides a structured and documented way to help get the most out of funds spent on the infrastructure.

1.9 Summary

Asset management systems are being successfully used in the private, public, and quasi-government sectors to improve the decision-making process within these organizations. These systems are effective means for improving the profitability of an organization, or the cost-effectiveness of the utilization of funding allocations.

Ultimately, it is the objective of both private and governmental organizations to improve the services provided to its customers, whether through the more timely distribution of a product or a smoother road to travel on. The use of asset managment provides agencies with the tools necessary to improve the services provided to its customers in the following ways *(2)*.

- Improved convenience
- Improved service (e.g., comfort, reliability, and safety, in a transportation context)
- Savings passed on from the owner/operator to the customer
- More accessible facilities and services due to more efficient operation

The practioners of pavement management can benefit through repeated dialogues with agencies practicing asset management. The changes in our government at the national and state level, and the accountability required of elected and appointed officials, are changing the way transportation agencies must do business. Those agencies practicing pavement management, and using the outputs to improve the decision-making within their organization, can be proud of the fact that their technical and managerial approaches can be compared to the leaders in private industry - those agencies practicing asset management because it makes sound business sense.

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MODULE 2

PAVEMENT MANAGEMENT SYSTEMS OVERVIEW

2.1 Module Objective

This module describes the basic components of a Pavement Management System, as well as provides some historical perspective on the evolution of PMS over the last 20 years. In addition, it will discuss how the products of that system can be used as tools to aid in the development and decision making process for the pavement maintenance and construction program.

Upon completion of this module the participants will be able to:

- Describe the basic components of a PMS
- Understand the evolution of PMS since the 1970's
- List and describe some of the more prevalent products of a basic PMS
- Be able to describe in some detail the current state of practice in PMS

2.2 Importance of the Transportation System

The United States has the largest transportation system in the world *(1)*. It serves 260 million people and 6 million businesses. The sheer physical size of the transportation system is difficult to comprehend. There are over 6.4 million km (4 million miles) of roads. In 1995, cars and light trucks – the vast majority of personal vehicles – were driven over 3.5 trillion km (2.2 trillion miles) in the United States. Or in personal terms, the distance an average car traveled in 1995 equaled a journey nearly halfway around the earth.

Transportation is a major component of the economy, accounting for nearly 11% of the gross domestic product (GDP). It provides links between businesses, industries and consumers. Transportation and related industries employ 9.9 million people in the United States – a little more than 7% of the total civilian labor force.

The economic importance of the U.S. transportation system goes well beyond the nation's borders. It affects the ability of U.S. businesses to compete in the expanding global economy. Over time, international trade has grown in importance as a component of the U.S. economy. In 1995, total exports and imports of goods and services amounted to almost 25% of the GDP.

Trucks dominate the nation's freight transportation system, especially for shipping distances under 800 km (500 miles). Trucks moved nearly three-quarters of the value and almost 5.5 billion metric tons (6 billion tons) of freight of all shipments. Growth in truck traffic has been dramatic. According to the Census Bureau *(1)*, the number of trucks increased by 24% from 1982 to 1992.

The truck fleet appears to be getting heavier and traveling further. Between 1982 and 1992, the number of trucks with operating weights above 36,000 kg (80,000 pounds) increased by 180%. The total number of vehicle-miles traveled in this class also rose by 193%. Multiple-trailer combination trucks, which doubled in number, traveled the furthest, averaging 126,000 km/vehicle (79,000 miles/vehicle) in 1992.

The highway system in the United States is composed of :

- Interstate highways – more than 73,000 km (45,774 miles)
- Other NHS* roads – almost 180,000 km (111,237 miles)
- Other roads – over 6 million km (3.75 million miles)

** NHS = National Highway System*

Governments spent $116.5 billion on transportation in 1993. The federal share was about 31%, which included grants to state and local governments. Of the total, 60% of the expenditures was for highways.

Government revenues from gasoline taxes and other transportation-related taxes and fees totaled $85 billion, covering 73% of all transportation expenditures in 1993. States collected about half of all revenues, the federal government a third, and the remainder is collected by local governments. 70% of the revenues were generated by highways.

The relationship between economic growth and transportation infrastructure is reciprocal. Historically, transportation has played an important role in determining the regional structure and spatial character of the U.S. economy and continues to do so today.

Evidence suggests that public investments in highways and other transportation infrastructure reduce the costs of transportation and output, and contribute to economic growth and productivity. At the same time, changes in the economy affect the use of transportation facilities and services by households and businesses.

In recent years, a good deal of research has been conducted on the contribution of public investment in transportation to economic growth and productivity in the U.S. A majority of these studies conclude that public investment in highways reduces the costs of transportation and production, and makes a positive contribution to total economic output. Similar studies in Europe and Asia produced comparable results. In particular, these studies suggest that the return on the investment of a dollar in highway infrastructure generally has been greater than the return on a dollar of private capital investment.

However, the benefits of the transportation system come with costs – accidents, pollution, congestion and so on. Although safety, energy efficiency and emissions controls have improved, transportation policies, regulations, and technological advances are still racing to keep up with the continual growth in travel and goods movement.

The ability of the transportation system to meet our logistical and mobility needs with a minimum impact on our pocketbook, our safety and the environment depends on informed decisions by public agencies, private enterprise and individuals. Because transportation and the world it serves are constantly changing, informed decisions require continual updating of our understanding of the transportation system, how it is used, what it contributes, and what it affects.

This snapshot captures a wide range of information on the U.S. transportation system and its influences. But the picture is moving. As awareness of the unintended consequences has grown, ways are being sought to measure the direct and indirect costs of transportation and combine those measures into a framework that supports public decision-making. An understanding of both costs and benefits is necessary to enhance the efficiency and effectiveness of the transportation system, to reduce the negative side effects, and to consider equity – the distribution of benefits and burdens among groups in the population – in public decisions.

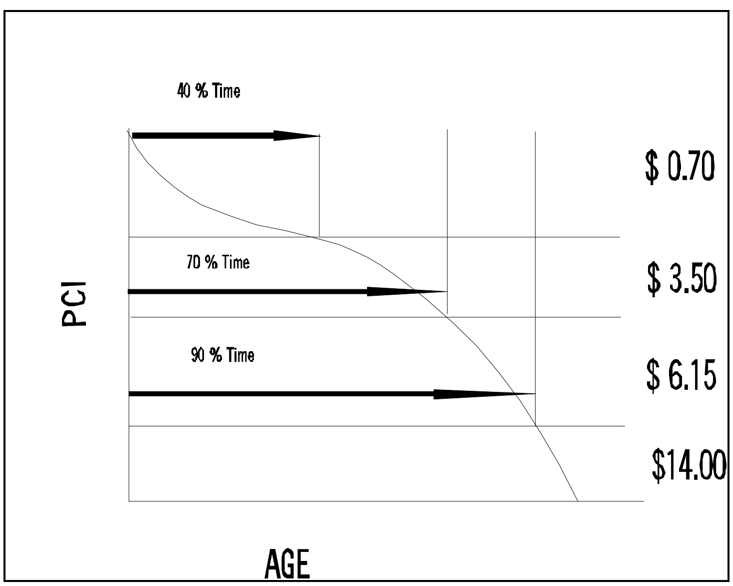
2.3 Importance of Pavements in Transportation System

From the previous section, it is apparent that transportation has an enormous impact on the U.S. economy, and on the lives of its residents. Pavements are just one part of the transportation system, and yet it is by far the most important component. Passenger-miles per person grew to 27,500 km (17,200 miles) by 1995. In terms of absolute distance traveled, the automobile overshadowed all other modes, growing by over 1.6 trillion passenger-km (1 trillion passenger-miles) between 1970 and 1995 *(1).*

The growth of trucks is of special importance to pavement engineers and managers since one major cause of pavement deterioration is truck traffic. (This is further discussed in Module 7.)

It is also true that all pavements deteriorate over time due to traffic and environment. Figure 2.1 is a curve that has often been used in presentations on pavement management systems (PMS). It shows the average rate of deterioration for an agency and the change in repair costs as the pavement deteriorates. It is evident from Figure 2.1 that if the earlier treatments were to be applied more often, the overall costs will be smaller if the pavement is repaired earlier rather than later.

Figure 2.1 Effect of treatment timing on repair costs (2).



Analysis by the Utah Department of Transportation indicates that it costs an agency less to have good roads than bad roads, if the roads are kept at any reasonable level of serviceability *(2).* This is based on the assumption that pavements will respond to preventive maintenance. Preventive maintenance is defined to include treatments applied to prevent or reduce the rate of deterioration, and it is limited to treatments which have traditionally been considered maintenance such as surface seals and thin overlays which do little to change the structural capacity of the pavement.

For preventive maintenance to be effective, pavements must be adequately designed to withstand traffic loads initially. Preventive maintenance treatments applied to pavement surfaces inadequately designed may delay the required rehabilitation for a short period of time, but in the long run they will not be very cost-effective. Many agencies own pavements that carry traffic loads for which they were never designed, and these must be structurally improved before they will provide the desired performance. Many agencies also have a backlog of maintenance and rehabilitation needs that must be corrected before they can fully adopt a preventive maintenance approach. These agencies must develop a program that works to improve those pavements in poor condition and structurally inadequate while also trying to keep those few pavements in good condition from deteriorating to the point where the less expensive treatments will not be effective.

The FHWA has long recognized the importance of pavements and the need to properly manage the pavement network. Numerous training courses, seminars, workshops and technical assistance are provided to states and other interested agencies. They also serve as a conduit to the American Association of State Highway and Transportation Officials (AASHTO), and support and augment the National Cooperative Highway Research Program (NCHRP).

2.4 Historical Perspective

Early Development: The earliest Pavement Management Systems (PMS) were developed in the mid to late 1970s as a direct result of the development of modern electronic computers and data base management systems. Prior to the use of electronic computers, in the late 1950's and the 1960's, agencies maintained their roadway route information on paper-based ledgers, strip maps, maps, and a system of archived files. This limited the amount of information that could be collected, stored, and retrieved.

The late 1950's and 1960's were also a time of intensive road building and pavement construction. Most agencies' construction programs were focused on the construction of new pavements rather than on the maintenance and preservation of their existing pavements. However, by the mid-1960's, some states had begun to change their construction program's emphasis from new pavement construction to pavement preservation *(3).*

At the same time, most state highway agencies converted to a computer-based roadway information system that was developed and maintained by a management information services group within each agency. These systems contained computer based files which contained basic roadway inventory data such as route number, location indicator, functional class, number of lanes, pavement type, width, shoulder type etc., at specific project, political, and accounting boundaries. The early management systems were mostly accounting driven. For example, the early maintenance management systems developed information on workforce time, equipment, and materials by specific task, time and location and construction management systems were developed for more automated contract accounting and contract payments systems.

Agencies have always managed some form of pavement preservation activity which could be considered pavement management. In most larger agencies, such as a state highway agency, the Agency was subdivided into regions, districts, or areas which normally managed the day to day road maintenance planning, design and construction projects. An Agency's pavement maintenance or rehabilitation project was developed from a list of projects developed at the regional level. The list of projects may have been developed based on a wide range of criteria ranging from perceived pavement condition (not measured) and engineering experience, to political necessity. In many cases, the list was developed based on relative pavement condition, maintenance activities, and engineering experience. Each region was allocated a specific amount of funds for each program cycle for their construction program, usually based on their proportion of highway miles of each function class and also with traffic levels sometimes factored in. Planning level cost estimates were developed for each project on the list, and projects were selected from the list until the allocated funds were consumed. The lists and projects were adjusted or massaged a bit to develop the actual construction program. As contract plans were prepared and awarded, some additional adjustments in the program were always required based on the final cost and scope of each project.

In the mid-1960's, a few agencies began to develop pavement condition surveys, and used the information from the surveys to help develop the project lists. The pavement condition data was stored and manipulated as part of the agencies management information system (*4,5*). By the mid-1970's a "systems" approach to managing pavements began to be envisioned and actively developed (*6,7,8*). Within a couple of years, several states and the US Army Corps of Engineers had developed and implemented a full PMS (*10,11,12*).

AASHTO GUIDELINES: In 1985, the American Association of State Highway and Transportation Officials published their first "Guidelines on Pavement

24). These Guidelines were prepared between 1982 and 1983 by members of the AASHTO Joint Task Force on Pavements who were involved in the development and implementation of a PMS in their respective state. The 1985 AASHTO "Guidelines" provided only minimal guidance as the body of the text consisted of only seven pages which introduced, defined, and supported the development and implementation of PMS.

Though only a few states were involved in actively developing and implementing PMS's in the early 1980's, a much larger number had developed, implemented, or adopted a PMS by the mid to late 1980's. In NCHRP Synthesis of Highway Practice 135 "Pavement Management Practices" (*17*) it was reported that, "Of the 53 agencies responding to the survey, 35 have some form of a pavement management system or process and 11 have either a partial system or they are in the development process." The remaining agencies indicated that they were planning on doing so. By 1994, NCHRP Synthesis 203 (*18*) reported that 58 of 60 agencies (50 states, 9 canadian providences and the District of Columbia) had a PMS in place.

In 1989, the FHWA established a policy that all states must have a PMS to manage their Federal Aid Primary Highway System (Interstate and Principal Highways) (*16*).

As a result of this policy, all states were required to have, and to use, a PMS as a one of the many conditions for federal funding.

In 1989, AASHTO formed a small Task Force on Pavement Management. Their task was to guide the development of a new and more complete set of guidelines on PMS. The new guidelines were prepared by Fred Finn and Dale Peterson through a special NCHRP project. The new "1990 AASHTO Guidelines for PMS" provided a more detailed set of descriptions and recommendations than the 1985 guide but the new guidelines were still limited in size as the authors were, from the beginning, limited to only 35 pages by the Task Force (*15*). The final guidelines totaled 48 pages with the body of the text consisting of a concise but complete 34 pages. The primary scope of the 1990 Guidelines for PMS was to:

- Describe the characteristics of a PMS.
- Identify the components of a PMS and the role of each component.
- Describe the steps recommended for development, implementation and operation of a PMS.
- Describe the products of a PMS which can help management in making informed decisions based on sound principles of management and engineering
- Define the role of communications in a PMS.

The 1990 AASHTO Guidelines for Pavement Management Systems still provide a very good description of a basic Pavement Management System and the typical modules that usually make up a PMS. The Guidelines will be used later in this section to provide an overview of the basic components of a pavement management system.

ISTEA: The scope of federal and state involvement in PMS expanded when Congress passed the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and required all states to have a PMS that covers all Federal-aid highways by 1995. The most significant aspect of this law was the expanded network coverage. FHWA's 1989 policy covered 313,700 centerline miles and ISTEA tripled that coverage, increasing it to 916,200 centerline miles. This expanded coverage translated into a need for significant coordination among state and local governments. For example, of the 916,200 miles covered, 365,200 are under local jurisdiction. In December 1993, FHWA issued a regulation covering all management systems. Section 500, Subpart B, of the regulation describes the ISTEA requirements for PMS. The following is a summary of the more notable issues of the regulation as described below (*16*):

- The regulation is non-prescriptive;
- Federal-aid funds are eligible for the development, implementation, and annual operation of a PMS;
- States must develop their work plan by October 1994, designed to meet the implementation requirements;
- Standards are included for the National Highway Systems (NHS);
- The PMS for the NHS must be fully operational by October 1995;
- The states have full flexibility to develop the standards for the PMS that cover the non-NHS routes;
- The PMS for non-NHS routes must be fully operational by October 1997; and
- PMS information must be used as input into the development of the metropolitan and statewide transportation plans and improvement programs.

Section 500.207, PMS Components, contains the components of a PMS for highways on the National Highway System (NHS). There are three primary components: data collection, analyses, and update. The components under data collection included the following:

- *Inventory*: physical pavement features including the number of lanes, length, width, surface type, functional classification, and shoulder information;
- *History*: project dates and types of construction, reconstruction, rehabilitation, and preventive maintenance;
- *Condition survey:* roughness or ride, pavement distress, rutting, and surface friction;
- *Traffic*: volume, vehicle type, and load data; and
- *Data base*: compilation of all data files used in the PMS.

The components under analyses include the following:

- *Condition analysis:* ride, distress, rutting, and surface friction;
- *Performance analysis:* pavement performance analysis and an estimate of remaining service life;
- *Investment analysis:* an estimate of network and project level investment strategies. These include single- and multi-year period analyses and should consider life-cycle cost evaluation;
- *Engineering analysis:* evaluation of design, construction, rehabilitation, materials, mix designs, and maintenance; and
- *Feedback analysis:* evaluation and updating of procedures and calibration of relationships using PMS performance data and current engineering criteria.

The 1991 ISTEA act and the subsequent FHWA regulations on management systems were modified in 1995 by the National Highway System Act. This legislation reduced the management systems requirements and reconfirmed that the requirements for PMS were non-prescriptive.

In a recent national workshop on pavement management (New Orleans, July 1997), a proposed resolution to support pavement management was discussed and drafted. Discussion on the resolution centered on the following issues:

- PMS is good business practice
- Objective measures and protocols for pavement condition are essential
- Local/regional criteria are necessary and appropriate
- Transparent modeling and analysis is desirable
- Need for top level management support

2.5 Basic Concepts of a Pavement Management System

The following is a brief description of the components of a Pavement Management System. This description is taken almost verbatim from the 1990 AASHTO Guidelines for Pavement Management Systems (*15*). Though the text of the Guidelines was prepared several years ago it still provides a very good overview of the basic components and characteristics of a PMS.

TYPICAL MODULES OF A PAVEMENT MANAGEMENT SYSTEM
(FROM CHAPTER 2 OF AASHTO GUIDELINES FOR PMS) (*15*): A Pavement Management System is designed to provide objective information and useful data for analysis so that highway managers can make more consistent, cost-effective, and defensible decisions related to the preservation of a pavement network. While a PMS can not make final decisions, it can provide the basis for an informed understanding of the possible consequences of alternative policies.

Two major levels of pavement management decisions should be included in a PMS; network and project. Network-level decisions are concerned with programmatic and policy issues for an entire network. These decisions include: establishing pavement preservation policies, identifying priorities, estimating funding needs, and allocating budgets for maintenance, rehabilitation, and reconstruction (MR&R). Project-level decisions address engineering and technical aspects of pavement management, i.e., the selection of site-specific MR&R actions for individual projects and groups of projects. A comprehensive PMS includes components to assist in both network and project-level decisions.

Figure 2.2 shows a schematic representation of the typical modules of a PMS. These modules are:

- Database which contains, as a minimum, the data required for PMS analysis;
- Analysis methods to generate products useful for decision-making; and,
- Feedback process which uses on-going field observations to improve the reliability of PMS analysis.

The remainder of this course will discuss each of these modules in detail.

The main choices for an analysis method, in an increasing order of sophistication, are: pavement condition analyses, priority assessment models, and network optimization models. A SHA may choose one of these methods for direct implementation or may develop the system in stages, starting with a simple method and upgrading to a method with a higher level of sophistication and capability, if and when deemed desirable based on agency needs and available resources. Both the required database and the feedback process will be affected by the choice of an analysis method. These two modules of a PMS must be designed carefully, taking into consideration the current and the potential future choice of the analysis method. Each PMS module is described below in terms of its purpose and input-output characteristics.

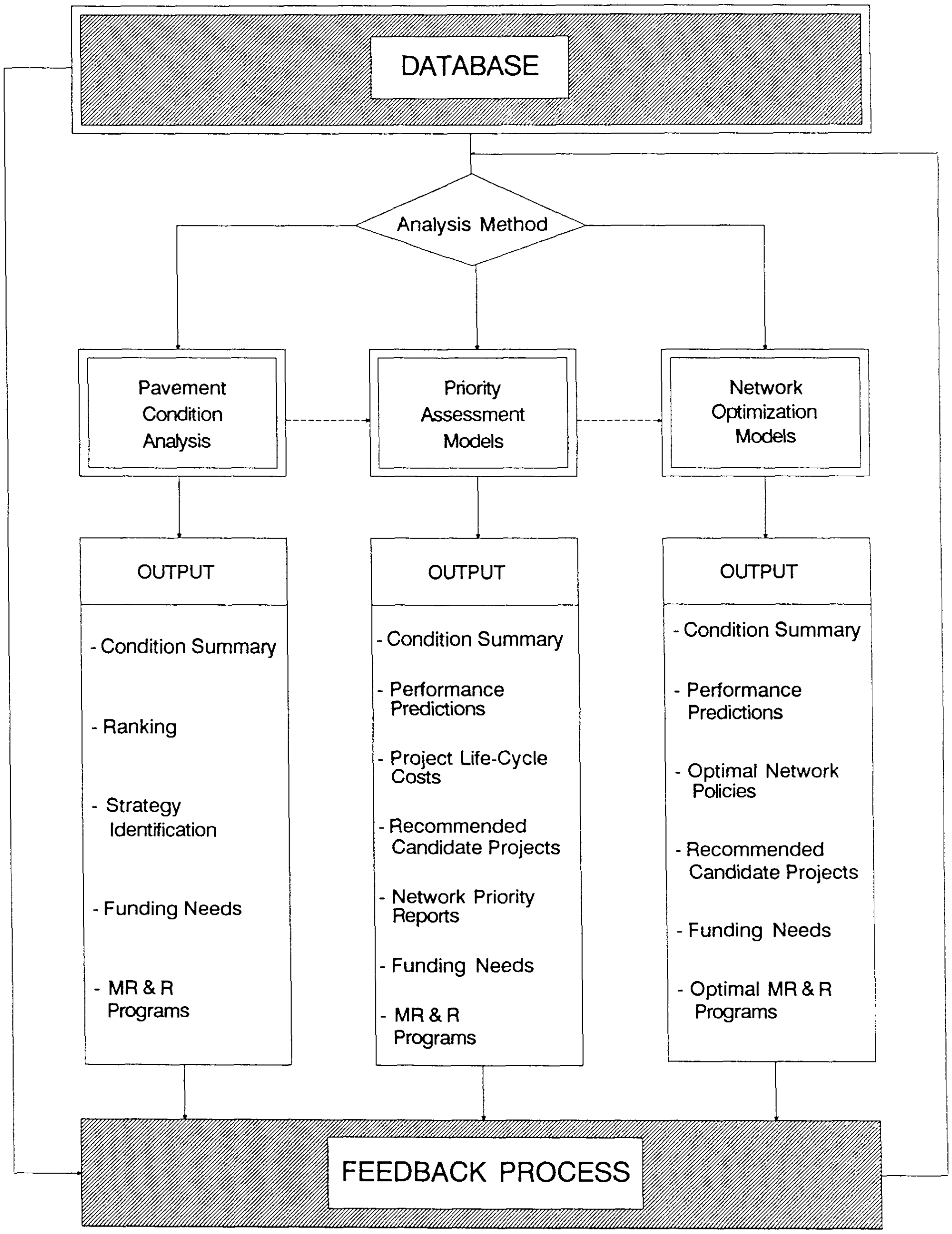


Figure 2.2: A Schematic Representation of PMS Modules

Database: The database is the first building block of any management system, since the analysis used and recommendations made by a management system should be based on reliable, objective, and timely (current) information. The major categories of input data essential for a PMS are:

- Inventory,
- Information relative to pavement condition,

- Construction, maintenance and rehabilitation history,
- Traffic, and
- Cost data.

A number of optional categories could include information concerning design, materials, accidents by location, and geometrics.

The database module supports the information needs of the other two PMS modules; i.e., analysis method and feedback process. It may also be useful to other information systems which may be or have been developed by a SHA. By using the information in the database, useful reports can be generated, such as:

- *Deficiency reports,* which identify pavement segments with a given type of distress (such as cracking, rutting, faulting, roughness, etc.) exceeding a specified threshold level
- *Performance histories*, which display the variation of a given type of distress as a function of age and traffic for specific pavement segments
- MR&R actions
- *Pavement inventory* by type and area as examples. A method of ranking pavements based on severity and extent of specific types of distress can be developed based solely on information in the database.

Analysis Method: A variety of methods are available to analyze pavement performance and cost data to identify cost-effective MR&R treatments and strategies. "Treatment" refers to a single action selected to correct specific pavement deficiencies. A strategy can refer to a plan involving a combination of treatments to maintain the network in a serviceable (acceptable) condition for specified time (analysis period); it can also apply to a series of treatments for maintaining a project in a serviceable condition for a specified time. The analysis methods can be divided into three broad categories based on the degree of formal analysis used to determine cost-effective MR&R strategies. The three categories, with an increasing degree of formal analysis, are: (1) pavement condition analyses, (2) priority assessment models, and (3) network optimization models.

The choice of an appropriate analysis method depends on a SHA's needs and expectations from a PMS, and the resources (data, staff, computers, funds, etc.) available for development and eventual long-term usage. Also, the methods of analysis are not necessarily unique to any one of the three categories indicated. For example, user benefits and agency costs, discussed herein under the priority assessment method could, and often do, apply to pavement condition analysis and would, in most cases, apply to optimization models.

At the start-up of a PMS, a SHA may choose the option of staged development by initially selecting an analysis method compatible with resources and needs and subsequently upgrading to a method with increased capabilities. An agency can, of course, decide to proceed directly to its ultimate goal if resources are available.

It should be noted here that the three analysis methods represented a cross-section of the analysis methods that were used by various SHA's at the time the AASHTO Guidelines were prepared. Though all three levels are still valid, most SHA's have now progressed to using the second and third analysis method, and many are developing the capacity to use the third analysis method (network optimization models). In a 1996 FHWA survey of state PMS practice, 14 states indicated that they were currently using the Network Optimization Method, and 17 additional states indicated that the Optimization Method was under development.

Pavement Condition Analysis: This method of analysis combines the pavement condition data for individual distress types, with or without roughness, into a score or index representing the overall pavement condition. The pavement condition score is generally expressed on a scale of 0 to 100, with 100 representing the best pavement condition and 0 representing the worst pavement condition. Alternate methods can be used to develop a combined index or score; however the 0 to 100 scale is the most prevalent. The calculation of the pavement condition score requires an assessment of weighting factors for different combinations of the severity and extent of each distress type. A combined index has several useful applications:

- It is a relatively simple way to communicate the health of the system to upper management, planners, and legislators
- Used as one factor, or the only factor, in a priority rating scheme
- Used as a technique for estimating average costs to maintain, rehabilitate, or reconstruct a candidate project; e.g., pavements with condition score of 50 will, on average, require x dollars to repair.

The outputs from this module can include:

- Ranking of all pavement segments according to types of distress and condition scores as a function of traffic or road classification
- Identification of MR&R strategies, which define a set of criteria (e.g., combinations of different distress levels and traffic) for assigning a particular action to each pavement segment
- Estimates of funding needs for the selected treatments.

The outputs are indicative of current needs based on current conditions. A prediction model is not necessary for this module; however, multi-year strategies and costs are not available from such systems unless assumptions are made regarding rates of deterioration and associated costs.

Priority Assessment Models: This analysis method uses a “bottom up” approach in which optimal MR&R strategies for individual projects are first determined based on life-cycle costs (*17*) over an analysis period of 20-30 years, or at least one major rehabilitation treatment. Projects can then be prioritized, at the network-level, using a variety of methods. The benefit/cost ratio and measure of cost effectiveness are the two most prevalent ways to prioritize; however, alternate schemes are possible. The project-level analysis includes models to predict pavement conditions as a function of such variables as age, present pavement condition, traffic, environment, performance history, and the treatment selected. Alternative strategies, including current and future actions, are evaluated for each segment and compared based on life-cycle costing analysis, benefit-cost ratio or cost-effectiveness, and the strategy with the highest priority over an analysis period is identified.

Benefits, when applied to a PMS, are generally categorized in one of three ways:

- Road user benefit.
- Agency benefits.
- A combination of user and agency benefits.

Road user benefits are defined (*19*) *"...as the savings in vehicle operation costs, travel time value, accident costs...that users of improved highway facilities...will enjoy."* Benefits can be quantified as the difference between user costs without improvements and user costs with improvements. The benefits divided by agency costs for improvement would reflect the benefit-cost ratio. At a project level, the strategy which provided the highest ratio would receive the highest selection priority. In a similar way, the set of strategies that would maximize benefits for the network, for a specific budget, would be used as a strategic planning tool to program network improvements (i.e., maintenance, rehabilitation, and reconstruction).

Agency costs include: (1) annual maintenance costs, (2) rehabilitation or reconstruction costs required during the analysis period, and (3) salvage value at the end of the analysis period. Costs used in evaluating a benefit-cost ratio are usually based on their net present worth or converted to equivalent uniform annual costs.

Road user benefits should be given some consideration when evaluating priorities of individual segments. Although methods for calculating user benefits have been developed, credible dollar values have not been established for U.S. conditions. User benefits are implicitly included in a PMS when specifying level-of-service goals or performance standards for different functional classes of highways.

Similar to the benefit-cost analysis**,** cost-effectiveness has been used to rank or prioritize the selection of projects. The difference is that a proxy, in terms of performance, is used to represent the benefit associated with a particular strategy. Performance or benefit can be measured in terms of the predicted area under a pavement condition (serviceability) versus time curve and cost is expressed as the equivalent uniform annual cost of MR&R treatments. Thus, the cost per unit of serviceability can be used as a cost-effectiveness ratio.

The output of this analysis method can include:

- A prioritized listing of projects requiring maintenance, rehabilitation or reconstruction.
- Costs for MR&R treatments.
- Estimates of funding needs in order to achieve specified network performance standards.
- Single-year and multi-year programs which identify segments recommended for maintenance, rehabilitation, or reconstruction, and the type, timing and cost of recommended treatments.

Optimization Models: Optimization models provide the capability for a simultaneous evaluation of an entire pavement network. The objective is to identify the network MR&R strategies which maximize the total network benefits (or performance), or minimize total network costs subject to such network-level constraints, such as available budget and desired performance standards. A network MR&R strategy defines the optimal treatment for each possible combination of performance variables such as: roughness, physical distress, traffic, environment, and functional class. This is a "top down" approach in which optimal network strategies are first determined and specific treatments for individual projects are then identified considering site-specific conditions and administrative policies.

Techniques of optimization, although somewhat new to highway engineers, have been used extensively in business decisions and are described in proceedings of the North American Conferences on Pavement Management. Optimization models in a PMS are used to analyze various management strategies and tradeoffs at the network level. For example, given a fixed network budget, should extensive and often expensive, treatments be applied on a smaller portion of the network, or should moderate, less expensive treatments be applied on a larger portion of the network?

The outputs from optimization models are essentially the same as those obtained from the prioritizing model, with only slight variations. For example, the optimization model does not identify segment priorities; instead, it identifies an optimally balanced MR&R program for an entire network to meet specified budget and policy constraints.

Feedback Process: Pavement management systems, similar to any other engineering tool, must be reliable in order to be credible. The feedback process is crucial to verify and improve the reliability of a PMS.

A measure of PMS reliability can be achieved by comparing:

- Actual costs of maintenance, rehabilitation, and reconstruction (available through contract bids and agency records) with those used in the PMS analysis.
- Field observations of pavement conditions and traffic with those predicted by PMS models.
- Actual performance standards achieved with those specified in the PMS analysis.
- Actual projects rehabilitated or reconstructed and the treatments applied with those recommended by the PMS.

If significant discrepancies are found between actual data and PMS projections, relevant PMS models and parameters should be revised appropriately.

At the start-up of a PMS, historical performance data may not be available to calibrate PMS models. Such calibration may need to be performed using engineering judgment and experience. With time, PMS models can be systematically calibrated using data from pavement condition surveys and construction records, thus improving the reliability of, and confidence in, PMS recommendations.

It should be noted that feedback information can also be useful:

- For agency research programs.
- To evaluate the influence of construction on performance.
- As a measure of the effectiveness of methods used for design of new and rehabilitated pavements.

2.6 Network and Project Level Pavement Management Systems
(From Chapter 3 AASHTO Guidelines for PMS) (15)

It is important to recognize that pavement management systems can be applied at two levels: network and project. At the network level, the primary objective is to provide information pertinent to establishing network budget requirements, allocating funds according to priorities, and scheduling MR&R actions. At the project level, the primary objective is to provide a first estimate of the preferred MR&R action for each project, its cost, and expected life cycle. In this chapter some important aspects of each level will be discussed, including products and applicable technology.

Network Level PMS: Specific products required to meet the objectives of a network level PMS include the following as a minimum:

- Information concerning the condition or health of the pavement network.
- Establishment of MR&R policies.
- Estimation of budget requirements.
- Determination of network priorities.

Evaluating the Overall Health (Condition) of the Network: The range of pavement conditions may be divided into discrete categories (qualitative) such as very good, good, fair, and poor. The proportion of segments (mileage) in a network in each of these categories can be used as indicators of the overall health of the network. These indicators can be plotted against time to identify trends (i.e., is the proportion in the poor condition constant, decreasing or increasing?).

Numerical values obtained from combined condition indices can be used as an alternative (quantitative) measure of the health of the system. The choice between qualitative and quantitative representations is a management decision.

Establishment of Maintenance, Rehabilitation and Reconstruction (MR&R) Policies: Four methods are available for establishment of MR&R policies:

- Matrix.
- Decision tree.
- Life-cycle costing analysis.
- Optimization.

The *matrix* method matches a set of specific distresses with a set of appropriate MR&R treatments. The selection of a specific MR&R treatment is based on the dominant treatment which will correct all of the pavement deficiencies. The association between distress and treatment is based on engineering judgment accumulated from years of agency experience.

For a *decision tree*, important variables such as specific distress types, traffic, and functional classes, would be considered in selecting MR&R treatments. A tree-like diagram is developed which displays different combinations (branches) of selected variables at various levels. For each combination, an appropriate MR&R treatment is assigned in the same manner as that used for the matrix method (i.e., agency experience and engineering judgment).

The *life-cycle cost* method selects the MR&R treatments based on the least life cycle cost of a combination of treatments (strategy) required during the analysis period. Alternative strategies can be evaluated as part of this method. The cost components included in this method of analysis are: (1) construction, (2) maintenance between major rehabilitation treatments, (3) cost of rehabilitation treatment, and (4) salvage value at the end of the analysis period. In order to compare alternative strategies, life cycle costs are calculated using either present worth or equivalent uniform annual costs. An appropriate discount rate must be assigned in order to obtain credible comparisons.

The *optimization* method requires identification of an objective function, decision variables and constraints. For the PMS analysis, the objective function is usually one of the following:

- Maximization of user benefits.
- Maximization of network performance standards.
- Minimization of total present worth costs. Decision variables are the set of MR&R treatments. The constraints may include the total available budget, minimum network performance standards and/or minimum performance standards for different areas (i.e., districts). The optimization method identifies estimates of both short-term and long-term budgets needed in order to preserve the pavement network at or above prescribed standards.

Budget Requirements: The PMS will provide an estimate of budget requirements to preserve the pavement network at prescribed levels of performance. In most cases, the PMS will provide a one-year and multi-year estimate of requirements. In many cases the budget requirements will exceed the funding available. In such cases, one of the methods of prioritizing or optimizing will be needed in order to prepare a candidate MR&R program.

Determination of Priorities: There are many methods for establishing priorities, however, only the five most common are listed here. Alternate methods can be developed based on agency policies and administrative decisions. The five methods include:

- Matrix.
- Benefit-cost ratio.
- Condition index.
- Cost-effectiveness.
- Maximizing benefits.

The *matrix* method can be based on such factors as condition and traffic (i.e., the highest priority is given to those pavements that are in the worst condition with heaviest traffic).

The *condition index* method can be based on relative scores usually ranked from 0 (worst) to 100 (best). Priorities can combine condition score with such factors as functional class or traffic in order to develop a final list of projects.

The *benefit-cost ratio* procedure determines the benefit cost effectiveness ratio for each project segment where those segments with the highest benefit-to-cost ratio would have the highest priority. Whereas the previous methods are likely to favor a worst-first policy, the benefit-cost ratio could provide high priorities for pavements in fair-to-poor condition rather than always starting with worst condition.

The *cost effectiveness* procedure is similar to the benefit-cost ratio**,** except that the objective function is to maximize the performance as a function of cost. Performance, in this case, can be estimated from the area under the serviceability-time curve obtained from pavement prediction models. Those sections with the largest area above specified levels of service per unit cost would have high priorities. Costs are agency costs. This method does not require a worst-first approach.

The *maximization of benefits* is inherent in most optimization methods. However, methods for maximizing benefits can also be developed with prioritization and life cycle costs. For example, that group of projects from all candidate projects, which maximizes the combined benefit-cost ratio or cost effectiveness for a specified budget would be selected for MR&R treatments.

Project Level PMS: Once the results from the network MR&R program are established, it will be necessary to prepare plans and specifications for individual construction projects. Since the network level analysis only provided target MR&R treatments and expected costs for individual segments, additional information will be required before designs are finalized.

Detailed site-specific information pertinent to non-destructive test results, material properties representative of on-site materials and drainage considerations as well as detailed condition survey information are commonly required for the final design and cost estimate and for preparation of plans and specifications. Based on the additional information, the target MR&R treatments could be recommended from a project level PMS.

The objective function of a project-level PMS would usually be the same as that for a network; minimize life cycle costs, maximize benefit-cost ratio, etc. The project level PMS could consider additional MR&R treatments, which could be applicable or necessary, at a particular site. It could also use more accurate unit costs estimates based on project location. Thus, there would be some chance that the project level PMS would recommend an action different from that of the network system.

Data Collection for PMS (From Chapter 4 AASHTO Guidelines for PMS) (*15*): A pavement management system must have usable, accurate, and timely (current) information in order to produce credible results.

Inventory and identification data are generally obtained only once. Updates are required only when pavements are reconstructed to new standards and dimensions. Roadway geometrics, pavement type, location, and design traffic loads are other examples of data that do not require a yearly update. Information relative to pavement condition, actual traffic, surface friction, and others which may change with time, are collected on an established schedule or frequency. Data obtained for a network level analysis are generally less intensive and not as detailed as that needed for a project design (i.e., for preparation of plans and specifications).

Inventory Data: Inventory data are required for even the simplest pavement management system. Project identification including pavement type, route, functional classification, location (either tied to a GIS, Geographic Information System, or to an identifiable reference system such as mile post, link mode or state coordinates) is essential.

Specific types of information to be collected should be carefully considered during the planning phase. Information required for analysis, interpretation, and for preparation of reports, should be included in the inventory. Information not considered necessary for the PMS should be avoided. Some items to be considered for inclusion as part of the inventory are:

- Route number
- Functional classification
- Length
- Pavement type
- Pavement width
- Number of traffic lanes
- Shoulder type
- Shoulder width
- Layer thickness
- Construction history
- Rehabilitation history
- Maintenance history
- Sub-grade classifications
- Material properties
- Material sources
- Joint spacing
- Load transfer
- Resilient modulus
- Provision for drainage
- Climatic factors (precipitation, freeze-thaw)

In order to assure accurate locations for each item in the inventory, it is essential that a common reference system be used for all information gathered for a pavement regardless of the source of the data. The history of the construction, rehabilitation, and maintenance of the pavement is very desirable and may be required for the systems with more complex analysis procedures. The inclusion of information relative to material properties and sources, as part of the pavement history, provides a basis for evaluating design procedures and possible need for modifications.

Traffic: Traffic and load information is important for three reasons:

- § To determine priorities
- § To develop, calibrate, and use pavement performance models.
- § To select the maintenance, rehabilitation, or reconstruction treatment.

The types of traffic data required include:

- § Average annual daily traffic (to establish priorities).
- § Equivalent 18-kip single axle loads (for predictions and treatments).

Pavement Condition Survey: Monitoring pavement condition over time is essential for a PMS. Condition surveys provide information needed to evaluate the health of the network and the condition of any specific segment. Condition survey data collected over time will also be required if and when prediction models are to be developed.

There are four basic types of pavement condition information:

- Ride quality or roughness.
- Physical distress.
- Structural capacity.
- Safety.

Ride Quality: One of the major accomplishments of the AASHTO Road Test (1956-1960) was that it developed a concept or method for evaluating the performance of a pavement. The concept was based on the principle that the prime function of a pavement was to serve the traveling public. In turn, ride quality was used as a measure of how well pavements could serve the public (*20*). Studies made after completion of the Road Test have consistently indicated that ride quality could be correlated to pavement roughness. It has also been shown that roughness is not only a measure of user satisfaction (or dissatisfaction), but can also be related to user costs (i.e., vehicle operating costs and speed profiles).

Road roughness should be considered as a fundamental requirement for a pavement management system. There is a wide range of methods of measurement used to evaluate road roughness, either subjectively (ride quality) or objectively (roughness). For a SHA, the use of automated measuring devices to measure and record roughness is considered preferable to subjective ratings. Local government agencies, which do not have access to automated devices, have found subjective estimates of ride quality to be a useful measure of functional performance.

Methods for measuring roughness and interpreting roughness vary and are constantly changing as both equipment and analytical capabilities improve. Both response type roughometers, designed to measure vertical movement between the axle and frame of a vehicle (or trailer) and profilometers, designed to measure the longitudinal profile, have been used to evaluate roughness.

For comparison between agencies, the conversion to the International Roughness Index (IRI) could be considered as a useful means of summarizing roughness measurements (*21*).

Physical Distress: Physical distress is a measure of the road surface deterioration caused by traffic, environment and aging.

There are no national standards for procedures to be followed or equipment to be used for identifying pavement distress. It is, however, acknowledged that the type and cost of maintenance, rehabilitation and reconstruction will be significantly influenced by the type, extent and severity of distress.

Types of distress can generally be categorized into three classes:

- Fracture (cracking).
- Distortion (rutting corrugations, faulting).
- Surface wear or deterioration (raveling, spalling).

Specific descriptions of distress related to asphalt or portland cement concrete pavements may vary depending on the types of distress encountered in a particular area. However, the SHRP Distress Identification Manual has started to provided a form of national standard (*22*). In addition, the FHWA is in the processes of developing pavement condition data collection procedures under the “Pavement Performance Data Collection and Processing” project.

Methods for evaluating distress can vary widely, ranging from "windshield" surveys from a moving vehicle to automated equipment designed to measure and record distress in a prescribed way. The decision as to which method to use should be made as an integral part of the PMS development. The primary factors to consider are: applicability, cost, productivity, quality and quantity of the information obtained. The most important of these considerations are applicability, quality and quantity. For example, is there a sufficient amount of useful information and does the information represent field conditions?

Structural Capacity: Structural capacity is the ability of a pavement to accommodate traffic loadings with little or no cracking or deformation. The most convenient method of identifying structural capacity is through the use of non-destructive testing (NDT) equipment. Measurements of deflection, curvature, and joint efficiency can be used as an indication of structural capacity. Methods of interpretation have been developed by individual state agencies, industry and associations.

The inclusion of structural capacity and non-destructive testing in a PMS database will vary depending on the cost and usefulness of information acquired. Most network level pavement management systems do not include a routine requirement for non-destructive testing to evaluate structural capacity. However, most systems do require site specific evaluations of structural capacity, as well as estimates of remaining life, before deciding on an optimum maintenance and rehabilitation strategy at the project level.

Safety: The primary role of the pavement with regard to safety, independent of factors related to alignment or geometrics, is the ability of the pavement to provide an adequate friction between the road surface and the tire. The measure of friction is normally obtained with either the ASTM locked wheel trailer or a Mu-meter. Since most state agencies are required to periodically obtain friction measurements, such measurements should be included in the PMS database.

Pavement management systems should also include data with regard to accident locations with provisions for reporting locations with high accident rates.

Segments with low friction values and/or high accident rates should be identified in PMS reports. Such identification will allow the agency to make an in-depth evaluation on a case-by-case basis and to evaluate the need for, and scheduling of, a corrective action.

Historical: An important aspect of condition measurements is the ability to create a historical accounting of the rate of deterioration over time and under accumulated traffic loads (feedback). An understanding of what has happened in the past provides the basis for predicting what may happen in the future. The performance of different pavement or treatment types under various traffic or environmental conditions helps answer questions about what works, where it works, and why it works. Conversely, what doesn't work, where it doesn't work and why it doesn't work can also be identified to some degree from historical records. Historical condition data, under a wide range of conditions in the field, provide very useful information for research and can be used as a feedback to improve a pavement management system.

Frequency: Pavement condition can be determined at different frequencies such as annual or biennial. Factors that will determine the frequency are pavement age, rate of change in performance, cost of obtaining data, and the need for timely data.

Sampling coverage, whether partial, total, or random, should be designed to be representative of in-service conditions and should be extensive enough to track pavement performance at the network level.

Quality Control: Good quality control of inventory and condition data is essential to the success of a pavement management system. The data must be accurate, repeatable, consistent from location to location and from year to year, and representative of what actually exists in the field. Training of personnel, calibration of equipment and documentation of each, is necessary to assure long term confidence in the system and its results or output.

Methods should be developed to monitor the quality of information in the database. The most likely procedure would be to include a quality assurance requirement based on random sampling of information. Particular attention should be given to route locations, pavement areas and pavement conditions, since these items will play a major role in selecting MR&R actions and for prioritizing projects.

2.7 Current State of Practice in PMS

The state of the practice has evolved considerably since NCHRP Synthesis was completed in 1987 (*17*). As previously mentioned, the survey found that *"Of the 53 agencies responding to the survey . . . 35 have some form of a pavement management system or process and 11 have either a partial system or they are in the development process. The seven agencies that do not have a pavement management system and are not in the process of developing one all said they plan to establish one. Some of the weaknesses in present pavement management systems as identified by some of the agencies are: organization, life cycle costs, ability to predict performance, and the integration of pavement management systems with other data systems within the agency."* Many states have already gone through significant improvements to their PMS to satisfy ISTEA requirements.

NCHRP Synthesis 222 (*23*) provides a very good review of the more current state practice. In the summary, the following observations were made:

> "Highway agencies use a number of different pavement management methodologies to select projects and recommend preservation treatments for their highway networks. In some cases, agencies have highly sophisticated computerized processes in place. In other cases, agencies make decisions based on more traditional approaches to managing the network, including visual ratings and panel decisions regarding preservation actions. In light of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, which mandated the use of management systems (to include pavement management systems) for the selection of cost -effective strategies to improve the performance of transportation systems, many highway agencies evaluated their methodologies to determine whether they had the tools necessary to provide this type of information. However, it should be noted that the passage of the National Highway System (NHS) legislation in 1995 made the use of management systems optional rather than mandatory….
>
> Three predominant methodologies are discussed in this synthesis: pavement condition analysis, priority assessment models, and network optimization models. (Please note that these are the three basic methodologies described in the 1990 AASHTO Guidelines) "Based on data collected from a survey of agencies, pavement condition analysis was the most common methodology, with almost one-half of the agencies indicating use of this approach to some extent. The remaining agencies were equally divided among the use of network optimization models, priority assessment models, or some other approach to pavement management. With primarily three predominant methodologies being used, there are many similarities among agencies in the basic pavement management components of data collection and analysis. Even so, similar objectives for these components resulted in dramatically different data requirements and analytical techniques among agencies.
>
> Although pavement management has been practiced since the late 1970s, many of the agencies are still using manual and subjective approaches. Several highway agencies indicated that their pavement management systems are fully automated; however, the majority of agencies indicated than only a portion of their system is automated. Of those agencies, many reported that they would probably never fully automate their systems.
>
> ISTEA has greatly influenced the pavement management practices of a number of agencies. Agencies with previously certified PMS were required to be rectified by the Federal Highway Administration (FHWA), a process that required agencies to upgrade their existing capabilities. Issues that agencies were required to address in this regard included adding multi-year analysis, developing and using prediction models, providing PMS coverage for non-National Highway System federal-aid highways (including city and county streets) incorporating life-cycle costs, and considering alternate project or network strategies."

In addition to the NCHRP Synthesis 222, the FHWA conducted a survey of all the states in 1996 to document in some detail the status of their existing pavement management systems.

The following tables summarize responses to the 1996 survey and provides a detailed summary of the current practice in PMS.

Table 2.1 Pavement Management System - PMS Database: Inventory Data +

		Yes	Under Development	Considering In Future	No	No Answer
1.	Pavement Type	51	1	0	0	0
2.	Pavement Width	44	6	2	0	0
3.	Shoulder Type	37	9	5	1	0
4.	Shoulder Width	36	8	6	2	0
5.	Number of Lanes	50	1	1	0	0
6.	Layer Thickness	30	16	5	1	0
7.	Joint Spacing	17	10	6	18	1
8.	Load Transfer	16	7	6	22	1
9.	Sub-grade Classification	15	13	8	16	0
10.	Material Properties	9	14	18	10	1
11.	Resilient Modulus	3	12	16	19	2
12.	Drainage	12	7	13	20	0

Table 2.2 Pavement Management System - PMS Database: Project History

		Yes	Under Development	Considering In Future	No	No Answer
1.	Construction	41	11	0	0	0
2.	Rehabilitation	39	13	0	0	0
3.	Maintenance	28	18	6	0	0

Table 2.3 Pavement Management System - PMS Database: Condition Survey

		Yes	Under Development	Considering In Future	No	No Answer
1.	Ride	50	2	0	0	0
2.	Rutting	48	2	0	2	0
3.	Faulting	31	8	4	8	1
4.	Cracking	50	1	1	0	0
5.	Surface Friction	39	7	3	3	0
6.	Network-Level Deflection	5	9	15	22	1

Table 2.4 Pavement Management System - PMS Database: Distress Data

		Yes	Under Development	Considering In Future	No	No Answer
1.	High Speed Windshield Survey at 30 to 55 MPH	9	1	1	41	0
2.	Low Speed Survey at 0 to 10 MPH	18	0	0	33	1
3.	Combination of High and Low Speed	13	0	0	39	0
4.	35 MM Film Viewed at a Workstation	1	0	1	49	1
5.	Videotape viewed at a Workstation	20	5	6	20	1
6.	Distress Identification	37	2	4	9	0
	Manual with Pictorial References Used to Calibrate Extent and Severity					
7.	Fully Automated.	4	5	18	24	1
	Specify Equipment **					
**	See Distress Equipment Report					

Table 2.5 Pavement Management System - PMS Database: Traffic/Load Data

	Yes	Under Development	Considering In Future	No	No Answer
1. Does the PMS contain:					
a. Annual ESAL's	21	18	10	3	0
b. Forecast ESAL's	11	16	15	10	0
c. Cumulative ESAL's	10	18	17	7	0
2. Does the PMS have an ESAL flow map that is route specific?	7	14	19	11	1

Table 2.6 Pavement Management System – Investment Analysis: Prioritization Summary

	Yes	Under Development	Considering In Future	No	No Answer
1. Does the PMS office/unit produce a multi-year prioritized list of recommended candidate projects (this is considered a "first cut" list)?					
	31	20	0	1	1
2. What method does the PMS use to produce the multi-year prioritized list of projects?					
a. Subjective	4	1	0	44	3
b. Objective					
1. Priority Model	24	9	1	17	1
2. Incremental Benefit Cost	10	9	6	24	3
3. Marginal Cost Effectiveness	8	6	5	31	2
4. Optimization					
a. Linear Programming	8	10	6	26	2
b. Non-Linear Programming	2	1	6	40	3
c. Integer Programming	0	2	5	42	3
d. Dynamic Programming	1	2	6	39	4
e. Other (Specify)	9				43
3. If the answer to questions 2(b) is Yes or Under Development, who developed the Software?					
In House: 16	Contractor: 35			No Answer: 1	
4. Check the factors used to prioritize projects					
a. Distress	46	5	1	0	0
b. Ride	41	7	2	2	0
c. Traffic	38	12	0	2	0
d. Functional Class	33	9	3	7	0
e. Skid	19	7	7	18	1
f. Structural Adequacy	14	9	11	17	1
g. Other (Specify)	20				32

Table 2.7 Pavement Management System – Investment Analysis: Pavement Performance Monitoring and Projection Summary

	Yes	Under Development	Considering In Future	No	No Answer
1. Does the PMS monitor pavement performance?					
	37	13		1	1
2. Check all the pavement indices used to monitor pavement performance:					
a. Ride	38	9	3	2	2
b. Distress	42	7	2	1	1
c. Combined Index	26	10	4	12	12
d. Other (Specify)	16				36
3. Is load data (cumulative ESAL's) used to monitor pavement performance?					
	8	20	20	4	0
4. Does the PMS generate pavement performance curves?					
	25	21	5	1	0
5. Are the curves developed for?					
Family of Pavements	27	16	6	3	0
Each Pavement	19	13	11	9	0
6. Does the PMS monitor and predict performance using?					
Markov Transition	7	7	7	30	1
Semi-Markov Transition	1	2	9	39	1
7. Does the PMS monitor and predict performance using another method?					
	35			17	**
** No Answer counts as a no					
8. Does the PMS compute the Remaining Service Life of the network?					
	14	29		9	0
9. If the answer to questions 8 is Yes or Under Development, who developed the software?					
In House: 1	Contractor: 0			No Answer: 0	

Table 2.8 Pavement Management System – Investment Analysis: Preservation Treatment Summary

	Yes	Under Development	Considering In Future	No	No Answer
1. Does the PMS assign a preservation treatment to a candidate project?					
	35	17		0	0
2. If the answer to question 1 is Yes or Under Development, which groups of treatments does the PMS cover?					
a. Reconstruction	36	10		1	5
b. Rehabilitation	40	12		0	0
c. Maintenance	33	13		1	5
3. What method is used to assign a preservation treatment to a candidate project?					
a. Subjective	5	1	1	44	1
b. Objective					
1. Matrix	8	6	2	35	1
2. Decision Tree	18	14	5	15	0
3. Cost Benefit	10	9	7	25	1
4. Optimization Method Listed Previously	14	17	5	15	1
5. Other (Specify)	10				42
4. If the answer to question 3(b) is Yes or Under Development, who developed the software?					
In House: 15	Contractor: 36			No Answer: 1	
5. Does the PMS do a life-cycle analysis for the recommended preservation treatments?					
	20	26		6	0
6. If the answer to question 5 is Yes or Under Development, who developed the software?					
In House: 18	Contractor: 30			No Answer: 4	

Table 2.9 Pavement Management System – Investment Analysis: Products and Update

	Yes	Under Development	Considering In Future	No	No Answer
Products					
A. Is the PMS's multi-year prioritized list of recommended projects used as input in the development of					
1. Pavement Preservation Program	35	14		3	0
2. Statewide Transportation Improvement Program (STIP)	31	18		3	0
3. Transportation Improvement Program (TIP)	29	18		5	0
B. Is the PMS's multi-year prioritized list (first cut) compared to the final approve list of pavement preservation projects for reasonableness?	24	15	11	2	0
Update					
A. Does the SHA annually evaluate and update the PMS relative to the agency's policies, engineering criteria, practices, experience, and current information?	33	13		5	5

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MODULE 3

RELATIONAL DATABASES & LOCATION REFERENCING SYSTEMS

3.1 Introduction

This module covers several topics, all related to a PMS database. The module begins by introducing relational databases. This discussion starts with some of the basic concepts generally involved in databases, then moves toward explaining some of the issues regarding roadway data in a database. Following this, location referencing systems are presented, followed by an introduction on Geographic Information Systems (GIS) and how they relate to pavement management. Finally, a general description of Global Positioning System (GPS) is also included.

3.2 PMS Databases

What is a database system? It is a computerized record-keeping system consisting of the data itself and a set of programs to store, search, and manipulate that data. Databases are basic tools and processes for anyone who collects, sorts, distributes or analyses data. Pavement Management Systems are built around databases. The information needed to develop decision recommendations must be based on the date in the database. Some have used the analogy that the database is the heart of a Pavement Management System. The development of computerized database management systems, especially microcomputer based database management systems, has been a major contributing factor in the development, implementation, and maturation of pavement management systems

A number of database management systems are available for pavement management applications. There are many ways of organizing databases on a computer. Network databases, hierarchical databases, and relational databases are among the most popular. These types of databases differ in the way they physically manage the storage and retrieval of data. Hierarchical databases are perceived by the users as a tree in which they must start at the root and follow specific branches to get to a particular data element that they want. Network databases are similar to hierarchic ones except any particular data element can be attached to more than one branch. In a hierarchical example, the database would not look like a table at all. In this case, the tree would perhaps have district numbers at its root. Each district would then have a number of maintenance sections or branches. Each section of road would be described by data elements. To find the number of lanes of a particular segment of road using this arrangement, you would have to know what district the segment was in, then the maintenance section, and finally what highway. *(20)*

Relational databases allow the user to perceive the database as a collection of tables.

Of the three, the relational database is also the only one that is based on mathematical theory. In 1969, Dr. E.F. Codd published the first paper describing the application of relations (in a mathematical sense) to database management. Codd's most recent book, The Relational Model for Database Management, Version 2, *(16)* presents the relational model from a mathematical point of view.

In recent years, the relational model has generally become the de facto standard for database design. This is due to both the power of the relational model itself, and its ability to provide a standard interface called Structured Query Language (SQL) that allows many different database tools and products to work together in a consistent and understandable way.

Relational Theories and Definitions: No discussion regarding relational database would be complete without a brief introduction to the theory itself. Many casual database users incorrectly believe that the relational model gets its name because it can "relate" many tables of data. In fact, the relational model gets its name from the "relation" which in mathematical terms is a set. A relation has special properties in mathematics of which three are notable. First, all of its elements are tuples, which consist of attributes. Second, all tuples must be distinct from one another in content. And, third, the order of tuples is immaterial. *(16)*

Relational database presents the relational model to its users so they perceive the relation as a table, the tuple as a row and the attributes as columns.

Tables, Fields, and Records: The database *table* can be viewed as a set of rows and columns. In a relational database, the rows are called *records* and the columns are called *fields*. For example, a table of road sections in a PMS database might look like Table 3.1.

Table 3.1 Road Section Table

Section ID	From	To	AADT	Func_Class	Min_Width
d	0.0	1.0	1000	ART	1500
e	1.0	3.0	500	COLL	1000
f	3.0	5.0	100	ART	1500

Each row in the table is a record that contains all of the information about a particular road section, and each record contains the same types and number of fields: Section ID, From, To, and so on.

Keys: A *key* is a field or fields in the table used to access the data in the table. Keys are always indexed for fast retrieval. A key can be unique or non-unique, depending on whether duplicate values are allowed. A unique key can be designated as the primary key for the table, which designates it as the unique identifier for each row of the table. In the preceding example, for instance, the section identifier (Section ID) is the Road Section Table's primary key, because the Section ID uniquely identifies one and only one road section.

Relationships: A relational database is typically composed of more than one table. These tables can be related to one another in various ways. For example, the PMS database might also have a table listing all of the condition surveys performed in the pavement network (the Condition Table). Rather than repeating all of the road section information for each entry in the Condition Table, it could contain a single field that referred to the road section where the condition was surveyed, as shown in Table 3.2.

Table 3.2 Condition Table

Survey Sheet No.	Section ID	Year	% Cracking	Rut Depth
1028347	d	1985	10	0.2
8472039	e	1985	20	0.2
8437620	f	1985	15	0.2
6778902	d	1986	15	0.3

In Table 3.2, the Section ID field refers to the Section ID field in the Road Section Table, relating the condition to the road section on which it was measured. Notice that road section **d** (From 0.0 To 1.0) was surveyed in 1985 and 10% cracking was recorded. The same section was surveyed again in 1986 and 15% cracking was measured. The key that establishes the relation from the Condition Table is called a *foreign key*, because it relates to the primary key of a "foreign" table (the Road Section Table).

The type of relation shown in the preceding table is called a *one-to-many*, because one road section can have many condition surveys performed on it, but a particular condition survey is performed on one and only one road section. In a relational database it is also possible to facilitate relations that are *many-to-many*. For example, there may be a Construction History table that lists all of the contracts that are performed on the road network, as in Table 3.3.

Table 3.3 Construction History Table

Contract Number	From	To	Year	Work Type	Unit Cost
100	0.0	5.0	1955	Construct	100000
200	0.0	1.0	1986	Overlay	50000
300	1.0	3.0	1987	Overlay	50000
400	3.0	5.0	1988	Overlay	50000

In Table 3.3 we can see that there is a many-to-many relationship between road sections and contracts. That is, one road section can have many contracts performed on it, and one contract can perform work on many road sections. A many-to-many relationship is facilitated by creating two separate one-to-many relationships, with the common "many" table containing foreign keys to both of the other tables. This relationship becomes clearer, if we create a "junction" table by *joining* the Section ID field from the Road Section Table to the Contract Number field from the Construction History Table, as in Table 3.4.

Table 3.4 Example of a Junction Table

Contract Number	Section ID
100	d
100	e
100	f
200	d
300	e
400	f

Normalization: The task of the database designer is to structure the tables and relationships between them in a way that eliminates unnecessary duplication and provides a rapid search path to all necessary information. The process of dividing the database into separate tables and relationships that meet these goals is called normalization.

Normalization is a complex process (particularly in large databases) with many specific rules and different levels of normal form. A complete discussion of this process can be found in Ref. *(17)* and is beyond the scope of this discussion. However, normalizing most simple databases can be accomplished by following a simple rule of thumb: significantly reduce duplicate data. Notice the words "significantly reduce" are used rather than "eliminate." The reason for this is that sometimes it may be more work than necessary to eliminate all occurrences of duplicate information, particularly in small databases.

We have two occurrences of duplicate data in our example. First, the *From* and *To* data is repeated in the Construction History Table, and in the Road Section Table. Second, the Minimum Width, which is related to the functional class, is also duplicated in the Road Section Table.

With respect to the first duplication, since the Junction Table relates the Construction History Table to the Road Section Table, and since the *From* and *To* data for each road section is already stored in the Road Section Table, the *From* and *To* fields in the Construction History Table can be removed without any loss of information. This is a good example of performing "non-loss decomposition" described by Date. *(17)* See the Modified Construction History Table, Table 3.5 for an example of this feature.

Table 3.5 Modified Construction History Table

Contract Number	Year	Work Type	Unit Cost
100	1955	Construct	100000
200	1986	Overlay	50000
300	1987	Overlay	50000
400	1988	Overlay	50000

With respect to the second duplication, if there are 1000 arterial road sections in the network, each Arterial Minimum Width will appear 1000 times. To avoid this inefficiency, the table should be normalized by dividing it into two separate tables, one for Road Sections and one for Standards, as follows.

Table 3.6 Modified Road Section Table

Section ID	From	To	AADT	Func_Class
d	0.0	1.0	1000	ART
e	1.0	3.0	500	COLL
f	3.0	5.0	100	ART

Table 3.7 Standards Table

Func_Class	Min_Width
ART	1500
COLL	1000

Because the tables in our example PMS database are now normalized, changing the location for a particular road section, or changing the minimum width for a particular functional class can now be accomplished by changing a single record.

To reiterate an extremely important fact, this example is given only to present the ideas and concepts involved in creating and normalizing a relational database. It should not be used as a guide for building a custom PMS database. This process is not as trivial as the example implies.

Structured Query Language: No discussion regarding relational databases would be complete without mentioning Structured Query Language (SQL) SQL is commonly pronounced as “sequel” rather than “ess cue ell,” although both pronunciations are acceptable. SQL is the official standard language for dealing with relational systems and is defined by an ANSI standard.

SQL is supported by most commercial database products although specific implementations of SQL have minor variations from the defined standard. However, the overall structure and functionality of the language is very consistent from vendor to vendor. If a programmer has used any implementation of SQL, transition from one product to another will not be difficult.

SQL is a “non-procedural” language. This means that the programmer issues a command requesting a result and SQL decides how it can best achieve that result.

The SQL language is composed of commands, clauses, operators, and aggregate functions. These elements are combined into statements used to create, update, and manipulate databases. SQL provides both data definition language (DDL) and data manipulation language (DML) commands. Although there are some areas of overlap, the DDL commands allow a programmer to create and define new databases, fields, and indexes, while the DML commands let a programmer build queries to sort, filter, and extract data from the database.

To give an example of what an DML SQL statement looks like, consider our the two tables presented earlier called the Road Section Table and the Standards Table.

If you wanted to see the *Section ID, From, To, AADT* and *Min_Width* values for all road sections with an AADT greater than 500, the SQL statement would be:

SELECT	[Road Section Table].[Section ID],
	[Road Section Table].[From],
	[Road Section Table].[To],
	[Road Section Table].[AADT],
	[Standards Table].[Min_Width]
FROM	[Road Section Table]
INNER JOIN	[Standards Table]
ON	[Road Section Table].[Func_Class]
	= [StandardsTable].[Func_Class]
WHERE	[Road Section Table].[AADT]>500;

Translated to English this statement reads: "SELECT (these fields) FROM (this table) and (that table) by JOINing (this table) to (that table) using common values in the Func_Class field, but only include those records from both tables when AADT is greater than 500." Notice that the statement does not say how to perform the join, it just says do it.

Data: When building a relational database, little regard often is given to the main ingredient of the database. That main ingredient is data. This section points out a few important facts regarding data. These facts do not necessarily have to be considered during the design and implementation of a PMS database, however, it is irresponsible not to mention them in the context of PMS database design.

Data Versus Information: Thus far in the discussion the terms "data" and "information" have been treated as interchangeable. In fact, there is, or ought to be, a clear distinction. This distinction is important because it highlights the need for software and the use of hardware. The term "data" refers to the values physically recorded on the hardware by the database management system. The term "information" refers to the meaning of those values as understood by the user. Software ought to allow the user to supply "information", store that information as "data" and allow the user to retrieve that "data" as "information" again. "Data" as it exists in the database management system on the hardware is meaningless without software. *(17)*

To help illustrate this point, the earlier example used the values of 1500 and 1000 for the minimum width and intentionally did not give the units. The values of 1500 and 1000 are valid as far as the database management system was concerned. It stored them and retrieved them on demand. However, any pavement engineer would have had a puzzled look on his/her face when examining them because they are obviously not in the traditional units of meters or feet. This minimum width data is therefore useless until the units are communicated.

Because of the confusion that would result in using these terms precisely, they will be treated as synonymous for convenience in the remaining text.

The VIISA Rule: The VIISA database rule is easily remembered by thinking of its acronym as the credit card. It says that database designers ought to consider the following items when designing and implementing a database: V*alidity*, *Integrity*, *Independence*, *Security* and *Accuracy*. Any database that is designed and implemented without regarding these items is doomed.

Validity: refers to the fact that the given value stored in the database is correct. To ensure this, the data must adhere to some test while being entered. Tests such as staying within certain limits, or belonging to a list of acceptable values, are common.

Integrity: refers to the fact that one value is the same throughout the database. When the same data is stored in two or more places in the database, it must always be equal. To ensure this, one piece of data should be stored only once or at most twice. The process of normalization is used to help with this. When the same data is stored in more than one place in the database, programs must be built to ensure integrity if they are not provided by the database management system. For instance, a relational database needs a guarantee of Referential Integrity, in which the data used for relating is always internally consistent. In the example used earlier, Referential Integrity would be violated, if the user entered a Value of “COLLECTOR” in the Standards table, because the Road Section table refers to it as “COLL.” Most modern database management systems provide functions to help maintain referential integrity. However, these are never automatically imposed; they must be intentionally specified by the user.

Independence: refers to the degree to which the data is isolated from its end use. If data is collected and stored for one specific use, that data is dependent on that use. In other words, the data is not independent. When data is not independent, it is typically difficult to apply it to other uses. In the example used earlier, a condition table (Table 3.2) was included which had road sections up to two miles long. This condition table was given in the context of a PMS database in which it is typical to aggregate the condition up to road sections that long. However, if this were the only database in the agency where the condition data were stored, and if the agency wanted to identify localized rutting problems, this data would be useless because the rut depth would be stored as a two-mile average.

Security: refers to the degree to which the data is exposed to danger. There are two areas of security: protection of unauthorized use and prevention of loss. To guard against these, a database needs a security system and a backup procedure. Failure to consider either is an invitation for a catastrophe.

Accuracy: refers to how closely the data value represents the truth. Roadway data is always an approximation of the truth. The required accuracy requirements of the data in the database must be defined and communicated. The database system (which in this context refers to more than just software) must ensure the data represents the actual situation at the indicated location and time to this defined requirement.

3.3 Roadway Data

Introduction: Now that a few general concepts regarding databases have been introduced, it is time to get into some specifics about why roadway data presents such a challenge to database designers.

In pavement management, the road sections being analyzed must be homogeneous. According to a commonly accepted definition, a homogeneous roadway section means a section over which the data describing that section is constant. This sounds clear and simple, but in real life the concept of homogeneous section is not that simple.

In a simple PMS database, an agency would have one table describing the road sections being analyzed. One row in this table represents one road section. These sections are typically called “control sections”, “uniform sections”, or “candidate project sections”. The biggest problem with the one table approach is to decide how long, or short the road sections should be. Two opposing issues are confronted. On the one hand, the table must define the sections sufficiently so the required validity and accuracy of the data can be maintained. On the other hand, the sections must be sufficiently long to represent reasonable projects to be analyzed by the PMS. In the end, the trade-off ends up forcing the user to break one of the most important VIISA rules, data independence. This rule is broken because the data is dependent on the original definition of the road section.

Contrary to the one table approach, a relational database offers the possibility of keeping the two issues separate. Since a relational database can consist of many tables, a PMS database can have a different table for each different type of data needed. Each table contains a different set of data that describes a different set of road sections. Hence, each table has a different definition for section lengths and homogeneity. The sections only have to be homogeneous for the data contained in that particular table. This does not break the data independence rule of VIISA.

Using this approach allows the user to define an entirely different set of sections with an entirely different definition of homogeneous whenever it is necessary to perform the pavement management analysis. In this case, however, a whole new level of complexity enters the database design stage. The issues associated with this complexity are discussed in the following sections.

Relating Two Road Section Tables: To begin with, relating roadway tables to one another is not a trivial process. Consider the following two tables which both have sections that describe the same road.

Table 3.8 Road Section Table One

Section ID	Road	From	To	AADT
d	A	0.0	1.0	1000
e	A	1.0	3.0	500
f	A	3.0	5.0	100

Table 3.9 Road Section Table Two

Section ID	Road	From	To	Maint Cost
q	A	0.0	2.0	100
r	A	2.0	5.0	240

Critically examining these tables reveals a number of problems.

First, there is a dependency between records within each table. Because the *To* address of one record is equal to the *From* address of the next implies that a value in record two is dependent on a value in record one. Recall from the relational theory given earlier that the first property of a relation (table) is that the tuples (records) are distinct from one another in terms of content *(16)*. This does not seem to be the case in these tables. Also, there is an implicit requirement that these records be kept in order to facilitate the dependency. Recall that the third property of a relation mentioned earlier is that the order of the tuples is immaterial. Therefore, by their vary nature, it seems as though the tables do not conform to the relational theory.

The second problem compounds the first. That is, these tables have a many-to-many relationship between them. According to the earlier discussion on normalization, we must facilitate this many to many relationship by building a *Junction* table. What should the junction table contain? There is nothing in common between the two tables except the road name. To make matters even more complicated, section **q** in Table 3.9 relates to section **d** and half of section **e** in Table 3.8 (as can be deduced from the *From* and *To* values).

Creating this Junction table is not as simple as it may appear. For example, it appears as though the following Junction table satisfies our needs:

Table 3.10 Junction Table

Section ID (One)	Section ID (Two)
D	q
E	q
E	r
F	r

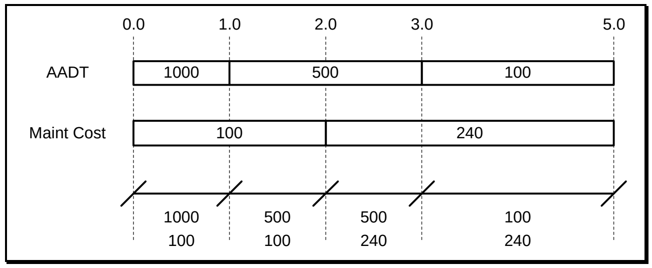
At first glance we have created two-one-to many relationships to replace the original many-to-many relationship. However, the fact that section **q** relates to half of section **e** is not obvious from the relationship. And, when things are not obvious, relational databases experience trouble.

These two problems illustrate why it is so difficult to build a relational database for PMS data.

After the relationship has been established, two processes are important: Dynamic Segmentation and Concurrent Transformation.

DYNAMIC SEGMENTATION: Dynamic Segmentation is a process where the road sections from two or more tables are split to form another table whose road sections are the smallest common denominator between the original tables. This facilitates the "show me" kind of reports which are common for PMS databases. It is easy to illustrate Dynamic Segmentation by drawing strip maps of road A from our example (see Figure 3.1).

Figure 3.1 Example of Dynamic Segmentation



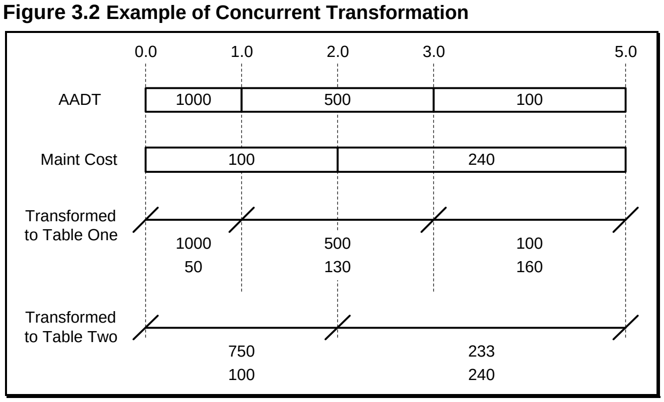
After performing Dynamic Segmentation, the process of identifying pieces of road with certain characteristics (i.e., doing a "show me" query) is easy. For example, "Show me all the pieces of road where AADT >= 500 and Maint Cost > 200." The answer is the piece of road from 2.0 to 3.0.

Concurrent Transformation: Unfortunately, Dynamic Segmentation does not accomplish everything needed to process disparate tables in a PMS database because, it is often impractical to perform life-cycle cost analysis on the smallest common denominator sections that result from Dynamic Segmentation. When three, four, five or more tables are joined using Dynamic Segmentation, the resulting sections become too small to serve any practical purpose other than the "show me" queries.

It is a common practice for a PMS to define sections we referred to earlier as "control sections", "uniform sections", or "candidate project sections" for the life-cycle cost analysis. These are different than the smallest common denominator sections resulting from Dynamic Segmentation. Therefore, if these PMS sections are to get their data from many tables in the PMS database, a process is required to perform this. Although similar to Dynamic Segmentation, this process is different and warrants a descriptive term of its own. The term "Concurrent Transformation"*(14*) is preferred.

Concurrent Transformation is also best described by drawing a strip map from our example tables (see Figure 3.2).

Figure 3.2 Example of Concurrent Transformation



The two lines at the bottom of the strip map show what the data would look like, it was transformed to the sections in table one and to the sections in table two, respectively. Notice how the values have changed during the transformation. The calculations performed on the values during Concurrent Transformation are based on the Transformation Class, which is discussed in the next section.

TRANSFORMATION CLASSES: During Concurrent Transformation different types of data are treated differently. Depending on the type of data, the associated values can be manipulated in several ways. For example, numeric data types can be summed or averaged while string data types cannot be. To facilitate a discussion the different calculations can be categorized into groups, called Transformation Classes. Although there are many Transformation Classes, seven common classes will be presented below: (1) weighted average, (2) sum, (3) maximum value, (4) minimum value, (5) statistical average, (6) first occurrence, and (7) most length.

Weighted average: is the most common Transformation Class for transforming numeric data values. The basic calculation is to sum the results of multiplying the value and length of the section the value is on, and then divide all this by the total length of all sections involved. A good example for this Transformation Class is in Figure 3.2 when the Average Annual Daily Traffic from Table 3.8 was transformed to the first section of Table 3.9. The value of 750 was arrived at using Equation 3.1. The length of the portion of the first section transformed from Table 3.8 is represented by the (1.0 - 0.0) expression in the equation. Similarly the length of the portion of the second section transformed from Table 3.8 is represented by the (2.0 - 1.0) expression in the equation.

Equation 3.1 Example of weighted average calculation.

$$750 = ((1000 * (1.0 - 0.0)) + (500 * (2.0 - 1.0))) / ((1.0 - 0.0) + (2.0 - 1.0))$$

NOTE: The milepoint *location reference method* (defined later) was used to remove unnecessary complications from the example. In fact, if another location reference method were used, the expression calculating length would be done by a function where the from and to locations were passed in as parameters. For example if milepoint 0.0 were address “a” and milepoint 1.0 were address “b” the above expression (1.0 - 0.0) would be replaced by something like: CALC_DIST(a,b). The CALC_DIST function would be provided by the *location reference system* (defined later) which would return the distance between address “a” and address “b.”

Sum: calculates the weighted sum of the values involved. This Transformation Class is also only used for numeric data values. The basic calculation is to sum the results of multiplying the value by the portion of the length being transformed compared to the length of the section the value is on. A good example for this Transformation Class is in Figure 3.2 when the Maint Cost from Table 3.9 was transformed to the second section of Table 3.8. The value of 130 was arrived at using Equation 3.2. The portion of the length of the first section transformed from Table 3.9 is given by the expression (2.0 - 1.0)/(2.0 - 0.0) in the equation. Generically, this portion can be expressed as (length of section being transformed / total length of section).

Equation 3.2 Example of the Sum Transformation Class

$$130 = (100 * (2.0 - 1.0)/(2.0 - 0.0)) + (240 * (3.0 - 2.0)/(5.0 - 2.0))$$

Maximum value: finds the maximum of all target values involved. This Transformation Class is also only used for numeric data values. In a PMS database, this Transformation Class can be used to calculate the maximum deflection. For example, if deflections stored according to 0.25km sections were transformed to 1km sections, the value transformed would be the maximum of the four source values.

Minimum value: finds the minimum of all target values involved. This Transformation Class is also only used for numeric data values. In a PMS database, this Transformation Class can be used to calculate the minimum skid number. For example, if skid numbers stored according to 0.25km sections were transformed to 1km sections, the value transformed would be the minimum of the four source values.

Statistical average: sums the values involved and divides by the number of occurrences. This Transformation Class is also only used for numeric data values. For example, the average snowfall can be calculated this way.

First Occurrence: finds the first occurrence of a source value if one were driving along the road. This Transformation Class is only used for values that are not numeric (i.e., string, date and logical data values.) For example, consider a PMS database with a table describing the local road name. If two local road name sections were transformed into one larger section, one way to get the local road name for the larger section would be to arbitrarily take the first local name encountered. Using similar logic a last occurrence Transformation Class can be defined.

Most length: sums all the lengths associated with each value involved. This Transformation Class is also only used for non-numeric data values. To perform the Transformation Class, the Concurrent Transformation process must keep track of the length associated with each source value. The value transformed would then be the source value representing the largest length within the target section. For example, consider a PMS database with a table describing the pavement type. If the target section consisted of more than one pavement type section, then the most logical way to transform the pavement type to this larger section would be to take the pavement type representing the largest portion of the target section.

Concluding Remarks: As illustrated in this section it is very difficult to define a relationship between two or more disparate road section tables. This difficulty is compounded when we add the concept of a road section table, which can include overlapping sections. Not to mention adding other tables that describe point objects such as accidents where many accidents can occur at one location and one accident can occur at many locations (at an intersection.) This discussion was intentionally kept brief so that the idea that the exercise is difficult can be made, rather than proving exactly how difficult it is.

The second point demonstrated in this section, is that even after the relationship has been produced, by its very nature road data requires some calculations that are not common for other types of data. Given the fact that SQL is “non-procedural” and that it does not have an inherent function for calculating the weighted average, writing an SQL statement to get the weighted average is extremely difficult. For example, the following SQL statement will give the weighted average of the AADT for the entire road A from our example Road Section Table:

```
SELECT     Sum([Road Section Table]![To]-[Road Section Table]![From]) AS Expr1,
           Sum([Road Section Table]![AADT] *
           ([Road Section Table]![To]-[Road Section Table]![From])) AS Expr2,
           [Expr2]/[Expr1] AS Expr3
FROM       [Road Section Table]
GROUP BY   [Road Section Table].Road
HAVING     [Road Section Table].Road = "A";
```

This example SQL statement was made simple by only involving calculation of one field from one table. Even still, a PMS database system requiring users to write such SQL statements would be considered “hard to use”. Not only does it require the users to understand SQL in some detail, but, it requires them to understand which data items require which transformations.

For these reasons, it is common for a highway agency to build a shell around their PMS database. Such a shell would manage VIISA rules, the relationships, the location reference system and the building of SQL statements. Building shells like this is expensive and time consuming. They are available ready made, however, and can be purchased.

3.4 Other Database Issues

Most agencies have several different and independent data systems. It is not uncommon for an agency to have an accident system, a traffic system, and a pavement inventory system to name a few. One of the most unfortunate issues about pavement management systems is the fact that they need many different kinds of data from many of these different systems in an agency. This need often gives rise to the need for developing a database that integrates all data together. Building an integrated database for just pavement management can be so daunting that many agencies elect to build an integrated database for the entire agency. Unfortunately, the development of many pavement management systems has been stopped until the integrated database is ready.

INTEGRATED DATABASE: To minimize expense all agencies should practice the data independence rule for all data and should place the data from all these systems in an integrated database. To develop this strong agency-wide data sharing, however, the agency needs effective methods of handling, sharing, and usage of data already available. To manage this, the agency usually has an organizational and technical unit whose main responsibility is the sharing of data.

An effectively integrated database insulates each contributor and end user of data from most of the problems of data interchange and collection. The integrated model is a high-quality solution to the data-sharing problem. The fundamental requirement of an integrated database system environment is that one system furnishes and receives information relevant to other management systems. The first step along this path is data independence.

The benefits of integration are substantial. Effective integration matches available data to each user's responsibility. A well-integrated database makes the task of finding the relevant data much less time consuming and more reliable. Integration provides a convenient means for each data-producing organizational unit to make its data available to others. The most significant economic benefit of integration is the use of historical data in estimations. When money is scarce, good information and strategy can stretch it further.

Integrated database systems can be implemented on many different platforms or combinations of platforms. Generally there is some central computer system (though this may be absent in a distributed database), separate computers or terminals for each user, possibly some shared intermediate computers, and data communication linkages among all these systems. The main differences in architectures are the extent to which computing power is centralized or decentralized, and the role of intermediate computers.

Stand-Alone: The first choice an agency can make regarding the integrated database is to have all software and data reside on a mainframe and all users dial in to the mainframe to use the system. These configurations are good for individual management systems, but, have so many practical limitations that they are seldom used for having all management systems access one central integrated database.

Distributed Database: In a distributed database data are physically located on many interconnected servers or workstations. Distributed databases do not require any centralized computer. Instead, each workstation automatically accesses the data it needs directly from the data's source workstation through automated protocols, at the moment when the data are needed. Each workstation must be relatively powerful and the network must provide high data-transfer speed. These system are relatively inflexible because database changes can occur simultaneously on every workstation.

Distributed databases are useful in situations like banking, where the local data and data processing can be distinguished from corporate data and data processing. They are not popular for developing and implementing integrated highway databases.

Client-Server: A halfway point between centralized and distributed computer databases systems is a client-server system. The client server configuration is very popular and seems to be the trend for integrated highway database development.

In this case a central database is resident on a central computer, but the server's only role is to act as a collection and distribution point for data. The server computer is fully dedicated to the database management task, so all reporting and analytical software is resident on the client workstations or on local-area network servers acting as clients.

The idea behind a client-server arrangement is that the power is focused where it is most needed, at the server. Client stations make requests for subsets of the data by passing the server an SQL statement. The server executes the SQL statement on the massive database and passes back to the client only the requested data. This way most of the processing is done on the server.

The workstations usually are microcomputers, the server can be mainframe, mini, or micro computer depending on the volume of data and the speed required. The user interface runs on the workstation, the database software runs on the server, and a network links them together.

The client-server arrangement is popular for developing integrated highway databases because it facilitates building the "shell" around the database as mentioned earlier.

3.5 Location Referencing

Much of the material presented in this section is based on a paper first published at the Third International Conference on Managing Pavements *(9)*.

Definitions: When discussing location referencing it is very helpful to define a clear set of terms and use them precisely. The following terms are used consistently in this chapter. These definitions will be expanded later when each issue is discussed.

The **location** of a point is the particular position that point exists on a road.

The **address** of a point on a road is a sequence of numbers and/or characters used to uniquely and unambiguously represent the **location** of that point. No two locations in the entire pavement network have the same address. Yet, the same location can have an infinite number of addresses.

The **primary direction** is the direction in which a road is said to "run."

The **positive direction** for undivided highways is the **primary direction**. For divided highways the positive direction is the direction of travel on each side.

The **negative direction** is the direction opposite to the positive direction.

The **offset** is a linear distance along the road that is often used in the **address** when the address is expressed in relation to a known point. A positive offset indicates the offset was measured in the **positive direction** from the known point. A negative offset indicates the offset was measured in the **negative direction** from the known point.

The **mile point** is the **offset** in miles from the beginning of the road in the **primary direction**.

The **mile post** is a post placed along the road, with a number placed on it representing the **mile point** of the post.

The **reference post** is a post placed along the road, with an identification number that is unique to that post.

The **reference point** is a point on the road which can be easily identified and whose identification number and **location** is known.

The **location reference method** is a set of procedures used in the field to identify the **address** of any point.

The **location reference system** is a set of procedures used in an agency to manage all aspects of location referencing.

Location Referencing Systems: The most important issue regarding location referencing is to make a clear distinction between a location reference system and a location reference method. National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 21, *(10)* defines the difference between system and method when it states:

> *There is a definite distinction between a highway location reference system and a highway location reference method, the former being a larger set of office and field procedures that includes the latter. The method is seen by the user in the field as a way to identify a single location; i.e., to reference a specific position with respect to a known point. The system is seen as the procedures that relate all locations to each other. It includes techniques for storing, maintaining, and retrieving location information.*

To manage location referencing a highway agency must have one, and only one, location reference system. A location reference system, like all information systems, requires separate components to acquire, store, manipulate, retrieve and distribute information. Typical location reference systems are a mixture of manual procedures for data acquisition and distribution, and computerized procedures for data storage, manipulation, and retrieval.

A well conceived location reference system will have several computerized functions. These functions must provide some basic information required for manipulating location information. Three of these functions are worth noting.

The first function, is **CALC_DIST**. The purpose of this function is to calculate and return the distance between any two addresses. For a simple location reference method such as mile point, the distance can be calculated easily by hand; the user simply subtracts the offsets of the two addresses. In other location reference methods such as reference post, calculating the distance cannot always be done by hand, thus the need for such a function.

The second function a location reference system must have is **CONV_ADD**. This function converts the address for a location to any other address for the same location. This function is particularly useful in agencies using many location reference methods.

The third function a location reference system must have is **GET_ADD**. This function takes an address and an offset as input and returns the address for that location. GET_ADD is like the inverse of the CALC_DIST function. With this function a user will get the address for any location by giving the address for a starting location and an offset which is the measured distance from the address.

In addition to automated functions like the above, location reference systems depend on the manual components, acquisition and distribution. The manual functions are carried out by employees in the agency who communicate the addresses of points among one another and with the system. Since consistency in this communication is paramount to success, managing the manual component is a large part of managing the entire system. One way to ease this burden is to enforce a well conceived location reference method.

Unfortunately, many agencies regard the location reference system as a trivial necessity. Hence, training courses to show people how the system and the method works are often neglected. Today, few highway agencies have location reference training as a requirement for all employees. In fact, few states even publish a location reference users manual. An example of such a manual can be found in Indiana *(8).*

Location Referencing Methods: A location reference method consists of a mechanism to find and state the address of a point by referencing it to a known point. Its purpose is to communicate the location of a point through an address.

As stated above, the method must be viewed as part of a larger system and should be developed within that context. The method must be easy to use in the field. It must also have characteristics that support the system. The balance between these two requirements provides the key to success for any location reference system. NCHRP Synthesis 21 *(10)* states that the objectives for a location reference method are to provide a means for:

- designating and recording the geographic position of specific locations on a highway,
- using the designations as a key to stored information about locations, and
- uniformity in application of procedures through which various highway-related data observations are located.

Listing "uniformity" as an objective explicitly highlights the desirability for an agency to either use only one location reference method, or provide a location reference system that can accommodate many methods at once. This also shows that designating a location should be independent of the viewpoint of various organizational units making observations.

There are two quite different approaches to location reference methods, commonly classified as being either "linear" or "spatial". "Linear" location reference methods express the address in terms of a linear displacement along a highway. "Spatial" location reference methods express the address in terms of three dimensional coordinates.

Although much work is being done in spatial methods, the authors are unaware of any highway agency, which has abandoned a linear method in favor of a spatial method. Even if the agency has a functioning Geographic Information System (GIS) a linear location reference method is still required so the GIS can perform Dynamic Segmentation *(11)*.

Spatial Location Referencing Methods: Spatial location reference methods use a set of coordinates to identify the location of a point. These "geo-coordinates", as they are often called, are commonly expressed in either longitude, latitude and elevation, or in state plane coordinates and elevation. The driving force behind using geo-coordinates seems to be a desire to use GIS (Geographic Information System) technology. A common mechanism to get a spatial address is to use GPS (Global Position System) which is discussed later.

The advantages of spatial location reference methods are as follows.

- No physical marking is required in the field.
- Coordinates can be obtained electronically with a GPS receiver.
- Any address given in terms of coordinates is permanent since the location in a three dimensional space never changes.
- Any point can be automatically displayed on an electronic map.
- Addresses can be given for data located outside the road’s right-of-way using the same method.

The disadvantages of spatial location reference methods are as follows.

- It is difficult to assign the topological relationships between highway segments in a three dimensional manner. The concept of topology will be discussed later.
- It is difficult to detect measurement errors in the field.
- Communicating where a point is located is impossible without a map, or without a linear location reference method.
- The motoring public will not be able to use location referencing to chart their progress along a route.
- Calculating a distance between two points requires complicated three dimensional geometry.
- Users in the field must have a GPS receiver.
- GPS receivers do not work when there is overhead cover such as trees and bridges.
- Accuracy requirements are significantly greater than for any linear method, as small errors can result in the point being identified on an entirely different facility.

A spatial location reference method gives an absolute position of the location. This causes problems when calculating distances between two locations. For highway data the generally accepted distance from one location on a road to another is the distance one would have to travel along the road. Calculating the distance between two absolute positions gives a straight line or “as the crow flies” distance. The calculations for Dynamic Segmentation and Concurrent Transformation are all based on relative distances such as those supplied by linear location reference methods.

Linear Location Referencing Methods: The manner of identifying a known point, generally called reference point, usually distinguishes one linear location reference method from another. Existing implementations of linear location reference methods can be described using one or more of the following fundamental methods:

- Mile Point
- Mile Post
- Reference Point
- Reference Post

Subsequent sections in this chapter will discuss each of the four fundamental linear location reference methods.

Even though there are many different names, all linear location reference methods are fundamentally the same. NCHRP Synthesis 21 *(10)* addresses this issue in its concluding remarks:

> *To the casual user of a highway location reference method, there appear to be many widely different methods in use today. There is a tendency to "see" significant differences between methods on the basis of different names. To make matters more confusing, terms such as "straight-line diagram", "route log", "coordinates", "mile point", and even "mile post" and "reference post", are used rather loosely in connection with location reference methods.*
> *... there really is not a great deal of difference between the several most commonly used methods.*

All linear location reference methods rely on the fact that the location of one point is relative to some other point on the same road. This is good because relative distances are required for Dynamic Segmentation and Concurrent Transformation.

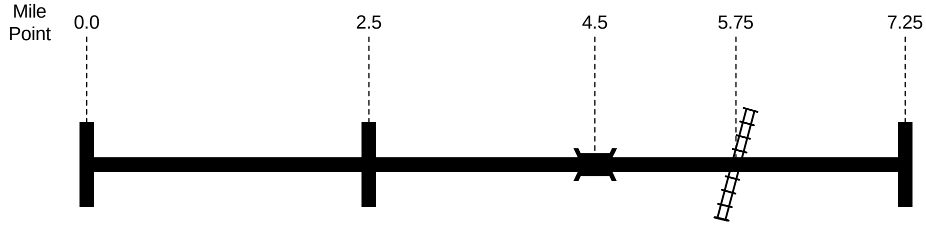
Many of the problems encountered with linear location reference methods are related to reproducing the distances between points. Any surveyor will attest to the fact that it is impossible to measure exactly the same distance between any two points repeatedly. This is why land surveyors measure the distance more than once and take the average. Unfortunately, highway engineers forget this and are constantly frustrated when the distances do not match. Many problems would disappear if these engineers would realize that and would take steps in the location reference system to accommodate it.

Mile Points: The mile (or kilometer) point location reference method is the most fundamental linear method of all. Most location reference systems employ the mile point method in some manner or another. Successful systems use the mile point method internally for functions, which relate locations to one another (such as the functions mentioned earlier).

This method assumes each road has one reference point located at the beginning of the road. The address of any point along the road is given as an offset. The offset being the distance of the point from the beginning of the road. Mile points are not physically identified in the field.

Mile point addresses are communicated with a format of "NNNN 999.999", where NNNN is road name and 999.999 is the mile point. Figure 3.11 shows a typical road that is 7.25 miles long and has five "incidents"; a start, a "T" intersection, a bridge, a railway crossing and an end.

Figure 3.11 **Example of the mile point location reference method.**



The advantages of the mile point location reference method are as follows.

- The distance between any two points on the same road is equal to the difference between the "To" and the "From" addresses.
- Special posts are not required.
- Easy to understand.

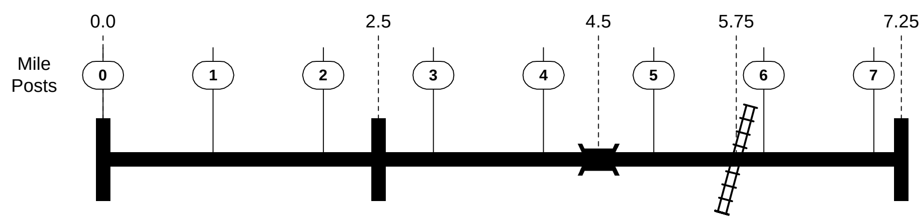
The disadvantages of the mile point location reference method are as follows.

- A user in the field must start to measure at the beginning of the road each time to get an address.
- Errors in measuring distances are more pronounced because of the large distances involved without “resetting” the odometer.
- Addresses are unstable because mile points change whenever the length of the road changes.
- Whenever mile points change on a road the location reference system must go to all files, including historical records, and renumber the addresses for all points on the road.

Mile Posts: The theoretical difference between the mile post and the mile point method is in the physical placement of posts at even mile points along a road. Each mile post must be labeled with a number that represents the true mile point at the post. The address of any point, then, is given by adding or subtracting the distance traveled from any post to the point in question.

The format for communicating the address of a point is the same "NNNN 999.999" as for the mile point. Figure 3.12 shows the same road as Figure 3.11, this time, however, the mile posts are also shown.

Figure 3.12 Example of the mile post location reference method.



The advantages of the mile post location reference method are as follows.

- Easy to use in the field.
- Motorists can use the posts to chart their progress along the road.
- A user has to travel at most one half mile to find the nearest post.
- Numerical sequencing of the signs provides users with easy orientation.
- A user can calculate the distance between any two points by subtracting the "from" address from the "to" address.

The disadvantages of the mile post location reference method are as follows.

- Maintenance forces must place, maintain, and work around posts.
- Posts must be located precisely at every mile.
- Posts must be replaced whenever the length of a road, or the unit of measure changes.
- If the posts ever become out of date, the method can no longer be a mile post method; it becomes a reference post method and <u>all the requirements of using a reference post method must be practiced</u>.
- Mile posts can be confusing on concurrent routes (the numbers on the posts represent the mile point for only one route, or there are a set of posts for each route).

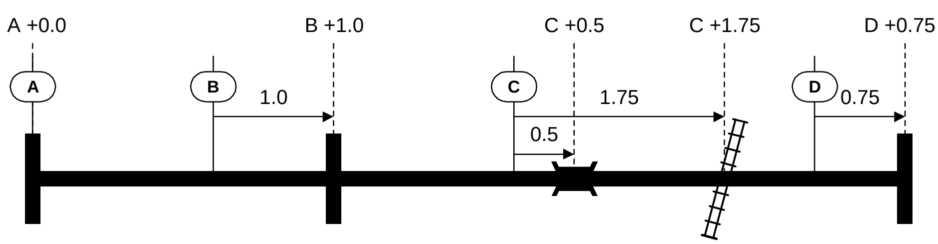
Reference Posts: The reference post method uses posts physically placed at various locations along the road. Each post has a reference number. In this method the reference point is identified by the number on the post. The address of any point, then, is stated by giving the route number, the distance traveled from any reference post to the point in question, and the direction.

To calculate the distance between any two points, all reference numbers must be related to a mile point. Although a reference post number will never change, the mile point associated with a reference post number may change. Maintaining the relationship between reference post number and mile point is the key to success. The distance between any two consecutive posts is maintained in a file for use by the location reference system functions mentioned earlier.

The format for communicating the address of a point using the reference post method is "NNNN XXX +/- 99.999", where NNNN is the route number, XXX is the reference number on the post, + or - indicates a positive or negative direction respectively, and 99.999 is the distance from that post.

Figure 3.13 shows the same road as the previous two figures, this time, however, reference posts are shown as well as the address of the incidents in terms of the reference post location reference method.

Figure 3.13 Example of the reference post location reference method.



The advantages of the reference post location reference method are as follows.

- Easy to use in the field.
- Addresses are extremely stable. Changes in route lengths, or in the unit of measure for distances do not affect the physical location of the posts or the validity of the post reference numbers.
- On concurrent routes a single set of posts applies to all routes.
- The distance between posts is usually small enough so users need not travel a long distance to find one.

The disadvantages of the reference post location reference method are as follows.

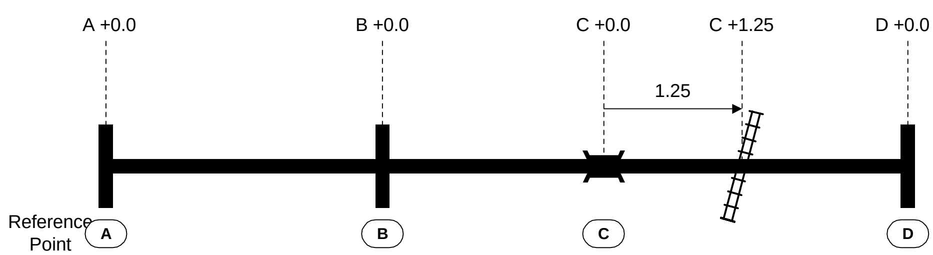
- Motorists may not be able to chart their progress along a route.
- Maintenance forces must place and maintain the posts, and work around them.
- Users and information systems must use a list to calculate distance between any two points.
- It is difficult to maintain and distribute the list of mile points for all reference posts.

Reference Points: The difference between the reference post and the reference point methods is physically placing posts in the field. The reference point method relies on assigning reference numbers to easily identifiable physical features such as bridges and intersections. The reference point is identified by a number contained on a list. Distance between any two consecutive points is given on the same list. The list is required in the field to find the number for any reference point.

The format to communicate the address of a point using the reference point method is identical to the reference post method: "NNNN XXX +/- 99.999".

Figure 3.14 shows the same road as the previous figures. This time, however, reference points are shown.

Figure 3.14 Example of the reference point location reference method.



The advantages of the reference point location reference method are as follows.

- Special posts are not needed.
- Addresses are stable, changes in route lengths, or in the unit of measure for distances do not affect the validity of the numbers for the reference points.
- On concurrent routes the reference points apply to all routes.

The disadvantages of the reference point location reference method are as follows.

- Cumbersome to use in the field.
- Reference points can often be located only at impractical distances apart on rural roadways.
- Motorists will not be able to chart their progress along the route.
- User and information systems must use a list to calculate distance between any two points.
- Maintaining and distributing the list of mile points for all reference points is difficult.

SELECTING A LRS: This section of the chapter presents five issues an agency should address when selecting an approach to location referencing: (1) balance between method and system; (2) experience of some DOTs; (3) stability of addresses; (4) institutional issues; and (5) the act of replacing one unit of measure with another.

Three general observations can be made. First, location reference systems based on a single location reference method are generally more successful than those involving many location reference methods. Second, location reference systems using posts are generally easiest to use in the field. Finally, location reference systems that require a list to be used in the field are generally more difficult to use and maintain.

Balancing Method Against System: In general, two issues must be balanced when selecting the appropriate location reference method for an agency: (a) the method must be easy to use in the field; and (b) the supporting location reference system must provide a mechanism to accommodate changes in addresses. It is desirable to reduce the impact of address changes so separate tables in the database including tables containing historical data can be easily related to one another. Creating an appropriate balance between these two matters is confusing because one is only obtained at the expense of the other.

For example, mile point and mile post location reference methods are attractive from the point of view of ease-of-use. However, these methods are extremely unattractive because of the instability of the address. On the one hand, mile point and mile post location reference methods are so easy to use in the field, they become trivial. On the other hand, very robust and complete location reference systems have to be built to ensure that any and all address changes are cascaded throughout all the data files in the entire agency. Usually this can only be achieved if the agency has all data in one integrated database.

Experience of Some DOTs: A true mile post location reference system must have a procedure in place to <u>ensure the posts are always located at exact mile points</u>. All posts beyond an effected point must be removed and replaced whenever a realignment activity occurs. Since this removal and replacement is seldom done, many agencies that started with a “mile post” method ended up with a “reference post” method. Yet, these agencies still call their method a “mile post” method, without having a location reference system in place to manage either. Mislabeling the method and lack of system procedures have resulted in much confusion.

Agencies still using these mislabeled mile post location reference systems are trying to force some procedures of a mile post location reference system to perform as those of a reference post location reference system while still employing the main characteristics of a mile post location reference method and becoming extremely confused in the process. (NOTE: the previous sentence was intentionally made confusing to highlight the point being made.) In these mislabeled mile post location reference systems, when a road's length is changed because of realignment an “adjustment equation” is introduced. The list of adjustment equations must therefore be carried in the field. Also, because of post placement errors some agencies have used the terms “short miles” and “long miles.” These are also accounted for by adjustment equations.

Use of terms such as “short miles” and “long miles” as well as use of adjustment equations illustrate the difference between a system and a method. The agency wants to get all of the advantages of using a mile post method and therefore has to introduce these concepts into the system. The result is often a mess.

Stability of Addresses: The impact of address changes is also a location reference system issue. The system must have procedures to accommodate changes in addresses swiftly and thoroughly. Since few agencies have integrated databases in place, percolating address changes to all existing information systems is difficult to perform automatically. Usually these matters are left to manual procedures and manual procedures are notorious for not taking place properly; especially without documentation or formal training in their application.

Therefore, an agency has two choices: automate procedures, or minimize address changes. Since providing the system with automated procedures requires an expensive integrated database, it is usually better to focus on education and address stability. Minimizing address changes is a location reference method issue.

Institutional Issues: Location referencing has a tremendous influence on virtually all areas of business in a DOT. <u>Anyone involved with DOT data must be familiar with various parts of the location reference system and all must be familiar with the method(s).</u>

Whenever any change is recommended, it is most often greeted with resistance. People, particularly those intimately familiar with the nuances of the current method and system, tend to resist change. If an agency wants to change its method, this resistance must be considered, planned for, and accommodated. In UDOT, this was accomplished through education seminars, and by forming a joint task force consisting of all major players, including the police. *(9)*

Changing Units: Changing the unit of measure for distances from English units to SI units will definitely have an impact on the location reference system. The size of this impact can be linked to how easily the location reference method can handle the change.

The conversion can be simple. In the reference post method, for example, all offsets in all files can be converted from miles to kilometers through a simple conversion program. Then, people in the field must start reporting all offsets in kilometers instead of miles.

However, the conversion can be complicated. For example, agencies using any form of the mile post method, mislabeled or not, must either remove and replace all posts, or convert their method and system to a reference post method. The agency must then make the same modifications in reporting offsets mentioned above for the reference post method.

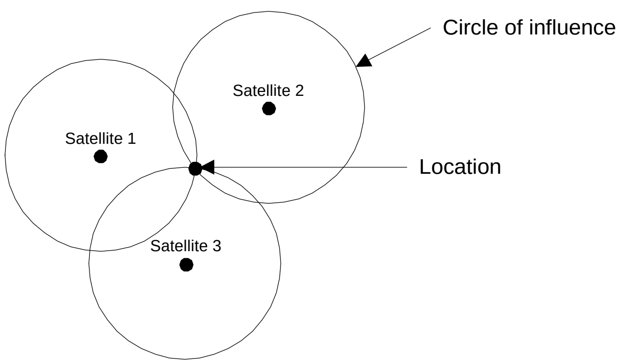
3.6 Global Positioning System (GPS)

Many years ago the US Department of Defense started placing a series of 21 satellites in orbit around the earth. These satellites form the basis of the Global Positioning System (GPS). At a cost exceeding $10 billion dollars, the GPS has the capability of giving the coordinates of locations to within 1 cm. *(7)*

CALCULATING A LOCATION: The basic idea behind using GPS is having a receiver that calculates its position using triangulation. The triangulation calculations require the receiver to know the exact position of at least four satellites.

Figure 3.15 shows a much simplified two dimensional view of how the GPS receiver can calculate its position. In fact, the circles in this diagrams should have been drawn as spheres; in which case the fourth satellite would have to be added. However, the triangulation calculation can still be demonstrated using the much simpler two dimensional model and three satellites.

Figure 3.15 Two dimensional view of GPS triangulation



Knowing the precise distance the receiver is from any satellite allows one to draw a "circle of influence" around it. The receiver must be located somewhere on that circle of influence. By adding a second satellite, the receiver must be at either of the two points where these circles intersect. Finally, the third satellite allows the receiver to know its position is exactly. It is where the three circles of influence intersect.

How does the receiver know where the satellite is? The GPS receives a radio signal from the satellite. This signal has the precise time it was sent "stamped" on to it. By knowing how fast radio signals travel, the receiver can use the "velocity times travel-time" equation to calculate the precise distance. Conceptually, it is as simple as that.

SOURCES OF ERROR: In actual fact, the radio signal does not have the time stamped on it. Rather, the satellites and the receivers are synchronized so they both produce the same signal at the same time. By comparing the signal received from the satellite with how long ago the receiver produced the same signal, the precise time can be calculated. This calculation can sometimes produce an error because clocks are not consistently precise.

Another problem encountered is that the velocity of the radio signal is not constant. It slows down when it hits the earth's ionosphere and when it hits the water vapor in the atmosphere. This slow down is one of the primary sources of error in a GPS measurement. These plus other sources of error such as minute changes in the satellite's position caused by the moon's gravity give rise to the fact that normal GPS gives an accuracy of within a hundred feet or better if you have a good receiver. *(7)*

DIFFERENTIAL GPS: A technique called "differential GPS" can bring the location accuracy to less than one meter. This technique involves placing a permanent GPS receiver at a known location in the area. This receiver gets the same signal from the satellite as the other receiver, but, since its location is known it can calculate a correction. This receiver then sends this correction to the other receiver, which makes the appropriate adjustments.

More precise techniques, extensions of differential GPS, have been developed by surveyors to bring the accuracy to within a centimeter.

OTHER GPS ISSUES: The accuracy of GPS can be purposefully degraded by the Department of Defense. This is called "Selective Availability" operational mode, which is designed to deny enemy forces from using GPS to their advantage.

GPS receivers need a clear line of sight to the satellites. This means that while traveling under a bridge or around tall buildings the radio signal can be "blocked" from view. This is another source of error.

USING GPS FOR PMS DATA COLLECTION: Traditional methods of collecting PMS data on a road involved linear location referencing. This has been often been criticized as being difficult and error prone. The advantages and disadvantages of different location referencing systems have been discussed earlier. Critics are convinced that automated GPS receivers would eliminate the problem completely. To examine why this sentiment is shared by many, one only has to go back and review the above chapter on location referencing. That chapter suggested that the problem was not so much a function of any particular location reference method. Rather, the problem seems to originate from the lack of understanding regarding the need for a location reference system and the proper use of whatever location referencing system is used.

It would seem that replacing a linear location reference method with a spatial method would not eliminate the need for a location reference system. In fact, it would probably require a more robust location reference system. Using GPS as a location referencing system would require the same consistency and attention to detail as any other location referencing system. Very few agencies have had success in this area..

Although the idea of collecting location data automatically is appealing, so far there is no evidence to support the argument that collection PMS data using GPS locations is a wiser investment.

GPS can provide accurate locations for certain reference points and provide an excellent interface to the GIS and automated mapping systems. The GIS systems require spatial information to be useful. GPS can provide this information accurately and efficiently.

For those agencies that deal with nonlinear pavements such as parking lots, storage facilities, and aprons, GPS is an excellent way to reference these facilities.

3.7 Geographic Information System (GIS)

A Geographic Information System (GIS) is defined as a system of hardware, software, data, people, organizations and institutional arrangements for collecting, storing, analyzing and disseminating information about areas of the earth. *(5)* When a GIS is applied to transportation the generally accepted name is Geographic Information System for Transportation (GIS-T).

An important distinction must be made between a GIS and automated mapping. The former is a system for collecting, storing, analyzing and disseminating geographic information, while the latter is a tool to show data on a map. Since the metaphor used by GIS is a map, the term GIS has been incorrectly applied to any system dealing with maps such as an automated mapping system. This lack of rigor in applying the term GIS has led to much confusion.

When Einstein said “Make the problem as simple as possible. But, no simpler.” he could have been criticizing this module. GIS and its related technology is a complicated subject; countless conferences, workshops, and journals are published every year to deal with its technology. Explaining GIS in detail is well beyond the context of this course. With that in mind, this module will first point out <u>some</u> major differences between GIS and automated mapping. These are presented in a very simple manner so that the essence of the issue is captured rather than the technological workings. Following this, the module concludes by relating the significance of these differences to PMS.

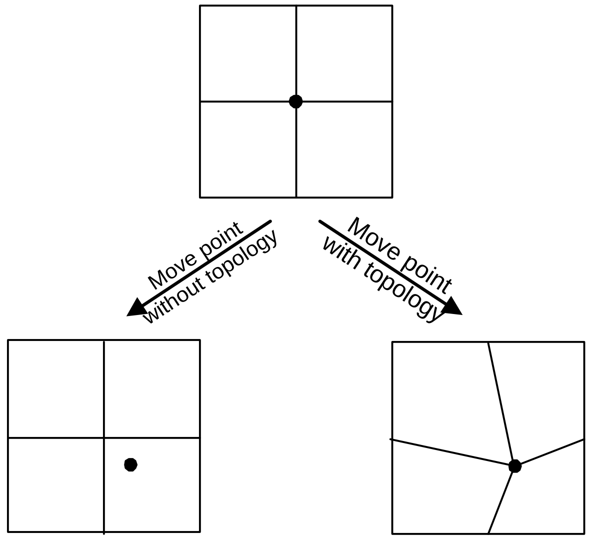
GIS: To begin with, a GIS consists of two broad categories of data: (1) attribute data and (2) spatial data. The GIS seamlessly integrates the two giving the user the capability of applying spatial analysis to the attribute data.

Attribute data consists of descriptions attached to an object. Attribute data is the same as the data stored in a traditional database. For example, a road section might have attribute data such as AADT, minimum width and maintenance cost, much the same as the earlier example.

Spatial data consists of geocoded objects (points, lines and polygons) that have an orientation and relationship in a two or three dimensional space. These objects have precise definitions and are related to one another with the rule of mathematical topology. *(1)*

Topology: Topology is an area of mathematics used to enforce relationships between objects. It is best explained with an example. Figure 3.16 shows three boxes. The top box has four polygons and a point. To demonstrate topology, we define a topological relationship between (a) the box and the respective sides of the four polygons that touch it, and (b) the point and the respective corners of each polygon that touch it. The two bottom boxes show the effect of moving the point. The box on the left shows the movement without using topology. The box on the right shows the movement using topology. The box on the right shows that since the corners and the point have a topological relationship, moving one also moves the others.

Figure 3.16 Example of a topological relationship.



Topology is an inherent feature of a GIS. Automated mapping does not inherently have topology. Topology gives GIS the power to build and maintain complicated relationships between spatial objects. To effectively use topology, great care must be taken to ensure the locations of the objects are precise. For example, if two roads sections (line objects) meet at an intersection (point object) then the location of the ends of the road sections must be exactly the same as the location of the intersection. Because of this need, much of the effort in building a GIS goes into preparing a Base Map.

The Base Map: A Base Map is defined as a map containing all the fundamental geographic features and location reference information required for, and from which other maps showing specialized information can be prepared. *(4)*

The source and content of the Base Map will vary among different agencies. The variations arise because of different needs for accuracy and the available budget. Some possible sources from which a base map can be built include TIGER files (Topographically Integrated Geographic Encoding and Referencing), aerial photography, or local hard copy maps. Building a Base Map and attaching all relevant objects to it is expensive and time consuming mostly because it requires extensive manual intervention called data conversion. *(2)*

Even though data conversion is expensive and time consuming, the payoffs are huge. Once completed, the GIS can begin “spinning its magic” by giving the users the capability of performing complex spatially related data queries in a seemingly intuitive fashion.

Integrating Data: The ability to integrate spatial data is the prime reason why an agency invests in a GIS. This integration is not limited to integrating road data. With a GIS all spatially related data such as land use and political boundaries can be integrated into the analysis. This expands the application of a GIS to the entire agency rather than for any specific department such as PMS within the agency.

AUTOMATED MAPPING: In an automated mapping system the map is just that, a map. The lines on the map have no topological relationships to one another. The automated mapping system does, however, have the capability of plotting the line on the map in different colors. Which part of which line to plot and which color to use must be passed into the system from an external analysis tool.

In an automated mapping system the agency plots lines on the map and gives those poly-lines a unique identifier or tag. This identifier can be any set of characters that uniquely identifies the line. To relate data in a database to the line on the map, the database has a table containing the line identifier. This table would be exactly the same as the example Road Section Tables described earlier, with the only difference being a column that contains the line identifier.

When a database answers a query, it can include the line identifier in much the same way as it can include any data attribute. The identifiers for the lines of the road sections are passed back to the mapping system with a command that says "plot these

Although this sounds simple, keeping the lines on the map in sync with the identifiers in the database is a task that must be done with manual intervention. Once designed, however, the procedures are fairly straight forward and easy to maintain.

APPLICATIONS TO PMS: Historically, traditional road data has been managed using linear location reference methods. This is perfectly satisfactory since roads are linear themselves and both the traveling public and highway officials are accustomed to locating themselves in a linear fashion. The question can be asked, "Does one need a GIS to manage traditional road data?" The answer is no. Linear data addressing is accurate enough and well understood, although not well practiced. This, however, is an institutional problem rather than a technological one.

A GIS is not needed to mange <u>traditional</u> road data for a PMS. However, if the analysis requires non-traditional data such as land use to be linked to road data, or the pavements are not linear, then a GIS is needed. Because spatial data is multi-dimensional the GIS systems can be used to perform analysis that includes proximity to nonlinear features such as district boundaries, political boundaries, work area restrictions and others that are most likely not defined in the linear referencing system of the PMS.

For example the GIS can be used to make adjustments to the work program developed in the PMS by combining projects of similar work type in the first three years of the program and take advantage of the saving by developing projects close together. GIS can also enhance project level analysis by including the concept of proximity, and analyzing data not traditionally found in a PMS such as political boundaries, landscaping, utility systems, and others.

Recall that the ability to perform Dynamic Segmentation and Concurrent Transformation are the two main requirements a PMS has with respect to road data. Both of these need a <u>linear</u> referencing system to be accomplished; whether performed by a GIS or just by an integrated database. Therefore, the need for linear data is not eliminated when one implements a GIS. The GIS does bring the ability to perform spatial analysis and include things that are not linked to the linear referencing system.

The point to be stressed regarding GIS is to use the correct tool for the task at hand. If, for example, the PMS department in an agency wants to simply show PMS data on a map, the expense of a GIS is not warranted because exactly that same map can be produced much more inexpensively with an integrated database and an automated mapping system. The GIS and automated mapping systems are very effective ways to present technical PMS data and analysis to decision makers.

This conclusion does not say, however, that if an agency has a GIS, the PMS department should not use it. Quite the contrary; if the GIS is already there, then make use of it, the expense of producing a database and linking it to an automated mapping system would be greater than just linking the PMS to the GIS.

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MODULE 4

INVENTORY & HISTORY

4.1 Module Objectives

This module will define what types of inventory and historical data should be collected, how it should be collected and how it is used in a PMS. Different types of data collected will be discussed as well as an introduction to ground penetrating radar for use in data collection. Upon the completion of this module, participants will be able to accomplish the following:

- Define types of inventory and historical data necessary for use in a PMS
- Be aware of different methods of collecting data
- Understand the use of ground penetrating radar (GPR) in a PMS to supplement construction layer history.
- Understand the importance of drainage on the structural adequacy of the pavement.
- Develop and use strip maps.
- Understand the importance of quality control (QC) on data collected.

4.2 Types of Inventory Data

One of the most important steps in the implementation of a pavement management system (PMS) is to develop an inventory of the pavement network. *The inventory process is the foundation of a PMS, and must be developed with a well-defined plan for the use of each and every data element collected.* To provide the PMS administrator with the support needed in the decision-making process, it is important to determine what data needs to be collected, how the data will be used, and how and when the data collection will be done. This ensures that the types of data collected can be used in the decision-making process, and eliminates the collection of needless data that is costly in both dollars and time.

Several factors should be included when deciding what data to collect:

- What decisions are going to be made
- What data is necessary to make those decisions
- Size of pavement network
- Type and characteristics of the agency
- Type and cost of data acquisition and processing
- Required accuracy of the data
- Required frequency of data collection
- Database capabilities

Data collection should be separated into two levels. The network-level data should answer the general planning, programming, and policy decisions supported by the network-level PMS. The project-level data should support decisions about the best treatment to apply to a selected section of pavement. As data are collected, selected elements can be stored to create a more complete database over time. However, a plan must be developed to keep that data current.

Only data elements needed to support decisions at the network-level should be collected at the network-level. Detailed data will be needed at the project-level and can be collected when the project-level analysis is completed.

When deciding what data to collect, there are two simple rules-of-thumb:

- Collect only the data you need!
- Collect the data only when you need it!

Decision-making policies should be supported with data that are:

- Relevant
- Reliable
- Cost effective to collect
- Cost effective to maintain

Typically, when an agency decides to implement a PMS, the first issue to be addressed is what kind of data should be collected. Usually, this is done through a committee composed of various personnel who will sit down and develop a “wish list” of data they would like to collect. Another common approach is to try to use data that already exists to build a PMS. Experience has shown that neither of these methods is effective when trying to design the inventory database of a PMS. Some hazards of defining inventory needs in this manner result in attitudes like “it would be nice to have the data” or “it might be useful someday.” Data collection is time-consuming, expensive to store, and expensive to analyze. Sifting through needless data will result in a slow, cumbersome PMS and a lot of wasted dollars.

The inventory will require a minimum number of data elements in order to be effective and will include some historical data. A typical PMS inventory at the network-level will include the following types of data *(1,5,6):*

- Section identification (see following section)
- Location - defines start and stop points (milepost, cross-street, etc.)
- Geometrics
- Pavement structure, construction and maintenance history
- Cost
- Traffic
- Drainage information
- Environmental data
- Proposed work or work-in-progress
- Other information

GEOMETRICS: The geometry defines the physical characteristics or features of the pavement sections. It can include lengths and widths of the section, functional classification (e.g. principal arterial, interstate), number of lanes, median width, shoulder width and type, cross-slopes, grade and curvature, and the presence of curb and gutters. This data is generally used in planning major rehabilitation projects to determine if reconstruction is required based on geometric considerations.

Pavement Structure, Construction & Maintenance History: In order to fulfill its purpose, a PMS must follow through from planning and programming design to implementation, including construction and periodic maintenance. Construction, of either a new pavement or rehabilitation of an existing pavement, converts a design recommendation into physical reality. Loss of performance, eventually leading to a need for rehabilitation, is identified within an ongoing process of data collection and evaluation. Such evaluation of pavement performance is also used for determining the current status of the pavement network..

Construction history is needed to identify the surface type and age of a pavement section. Maintenance and rehabilitation treatments that have been applied to the pavement are important not only for predicting how much remaining life a pavement may have, but also for predicting how well a treatment has performed.

For some agencies, the only pavement structure data available is the type of surface. This is inadequate for a good PMS. At the other extreme are systems that contain complete construction details of the pavement construction history. Pavement construction data includes information on the as-built properties of the materials, such as the results of concrete flexural strengths and asphalt concrete densities. Large variability of construction quality will result in poor performance.

In some cases, construction data will not be available in any form. If that occurs, the pavements can be cored or trenched to examine the structure. Generally, it is not necessary to have a separate program of coring to establish the pavement structure. The data can be collected as part of a structural evaluation, or other reasons.

Pavement maintenance data includes records of all maintenance activities that can affect the performance of the pavement such as crack sealing, patching and surface seals. A high level of maintenance makes it possible to extend the life of the pavement beyond the expected design life. The date and type of the last major maintenance or rehabilitation or any previous maintenance and rehabilitation history is also included.

Costs: The cost inventory should include data on the cost of new construction, maintenance and rehabilitation. It may also include user costs. Construction and rehabilitation costs can be compiled from records, estimates and surveys of recently completed projects, These costs should be updated on a regular basis. If an agency has implemented a maintenance management system, average maintenance costs can be determined by analyzing the data records. Otherwise, maintenance costs must be estimated based on the expected performance of the maintenance crews and the condition of the pavements. User costs are estimated based on traffic volumes, condition of the pavements, and models of vehicle operating cost.

Traffic: Traffic data is required in pavement management for the prediction of performance and the assignment of priorities during the selection of rehabilitation projects. For the selection of projects, a measure of traffic volumes is required. For highway agencies, the average annual daily traffic (AADT), with a breakdown into percent of trucks, is a common measure of the total traffic on a section.

Performance modelling, on the other hand, requires an estimate of the heavy vehicle traffic that generates the majority of the distress. For highway pavements, the usual measure is the 18-kip equivalent single-axle load (ESAL) used to estimate the quantity of vehicles that damage pavements or that the pavement has carried or is expected to carry. Traffic growth rates should be included for both the AADT and ESALs. This is further discussed in Module 7.

DRAINAGE: One critical element of pavement performance evaluation, that does not typically receive the attention it deserves, is the effect of drainage. A drainage system, or sometimes lack of, affects the structural adequacy of a pavement section and is critical with respect to seasonal variation influences. An agency implementing a PMS will want to assess what kind of drainage information will contribute to the decision-making process. Some issues that need to be resolved at the inventory planning stage are:

- How does drainage data impact maintenance or rehabilitation policy?
- How can drainage data be used in the decision-making process?
- What drainage data will need to be collected, (if any) for a road section?
- How often should that data be updated?

Drainage systems are complex and the drainage data collection is also complex. The first step would be how to identify the drainage system being used. The next step may include assessing the condition or functionality of that drainage system. This increases the data collection effort exponentially, as the consequences of poor drainage may not be apparent until a major flood event.

The effort and cost required to collect this information should be weighed against the ultimate use of the information. It should not be collected "because it is there" or "because it might come in handy someday." Once again, it is imperative that a definite plan for this data element be developed during the inventory planning stage, with a sound objective for its use in the analysis stage. The collection of needless data is time-consuming and costly.

ENVIRONMENTAL DATA: Environmental conditions can have a serious effect on the performance of pavements. When these conditions vary significantly across the geography of an agency's jurisdiction, a record of local environmental conditions can assist the pavement manager in predicting performance and in the selection of pavement rehabilitation strategies. There are several measures that can be used as an index of environmental conditions, such as the Thornthwaite index, seasonal rainfall, freeze-thaw cycles, freezing index, or regional indices developed by the agency.

PROPOSED WORK/WORK-IN-PROGRESS: Information regarding proposed work and work-in-progress assists the administrator in developing a maintenance and rehabilitation program.

OTHER INFORMATION: Any other data elements could include items such as pavement markings, side slopes, utility structures, culverts, signs, etc. Some agencies may already have a PMS and other databases. These other databases may include an infrastructure management system or a maintenance management system. Most auxiliary, non-pavement data should be left in these databases, and the PMS should only access that data as needed. This requires a common referencing system that limits the duplication of data collection and storage. This was previously discussed in Module 3.

4.3 Defining Sections

Once an inventory plan has been developed, the PMS network is ready for definition. This process divides the road network into segments called sections. These sections are the segments of roadway that will be used in the decision process. One general rule to keep in mind when sectionalizing is that:

The length or size of the section will determine the volume of data collected.

Long sections will generally be less uniform than short sections. Short sections require more data storage and typically must be combined together in project-level analysis, making it less likely that the agency will follow the network-level PMS recommendations. The final decision on size and method of sectioning should be based on selecting segments of pavement that the PMS manager will consider as single entity when planning maintenance and rehabilitation. The minimum number of sections that adequately define the road network will be the most economical and easiest to maintain.

When defining pavement sections, homogeneity is important and can be done using the following factors to assist in triggering section breaks:

- Changes in pavement type
- Changes in pavement structure (thickness, material, etc.)
- Changes in traffic (lanes, patterns, volume)
- Boundaries between previous construction projects (different projects reflect differences in design, materials, age, and other factors),
- Changes in natural subgrade characteristics

In addition, geographic or man-made boundaries may offer or force section limits:

- Rivers or streams
- City or township limits
- County lines
- Railroad grade crossings
- District, ward, or parish lines

Great care must be used to locate the section boundaries using the location referencing system. Proper use of the location referencing system is key to establishing the relationship between the sections and other data elements within the PMS database. The proper development of the location referencing system is discussed in Module 3.

Module 3 discusses in greater detail the advantages and disadvantages of reference points and posts. Each agency has to review their particular needs in order to select the most appropriate method. Milepost markers or special signs can be used to identify section boundaries in the absence of other landmarks. However, signs can be an additional maintenance expense, and may also be a potential safety hazard. Signs are not permanent; they can be knocked down and replaced in different locations. In rural areas, it is also a good rule-of-thumb to keep lengths shorter than one mile.

Highways in urban areas can also be divided into sections using intersections or blocks. The previous guidelines will help in determining whether one or several blocks are defined as a section. An important consideration is the manner in which the pavement area within the intersection is counted. In urban areas, intersections can account for a significant portion of the total pavement area. The intersection areas should be carefully designed to avoid duplication. This can be accomplished using the following:

- The area within the intersection may be treated as a separate section. This solution eliminates the problem of which cross street includes the intersection. Also, the stresses exerted on pavements within an intersection differ from those on the remainder of the block. The turning, stopping, and starting actions at intersections can cause pavement distresses that significantly differ from those which occur within a block. A disadvantage to this approach is that the number of sections is increased significantly. It may not be practical to use this procedure unless the inventory data is computerized.
- In urban areas where the street orientation is a rectangular grid, an arbitrary designation can be made as to which street sections will include intersections. For example, all North-South sections might include the area within intersections and East-West sections would exclude them.
- A hierarchy of street classes can be used for defining the street to which the intersection belongs. For example, an arterial would include all intersections along its length. A collector would exclude all arterial intersections. Residential streets would exclude both arterial and collector intersections. Residential cross streets could be managed with a combination of these last two methods, or with a notation on the inventory form as to which intersections are included.

Again, intersections must be included in the inventory but should not be duplicated at cross streets.

4.4 Identifying Sections

How a section is identified is probably one of the most critical elements of the PMS. It is important, when assigning section identification, to consider how the data will be stored and retrieved from the database. A simple, logical, linear system should be used in order to reduce the time and money spent handling the data. The section identification system selected must contain definite section start and stop points. There are several methods for developing identification systems. These are discussed below.

Existing Route Number: Although using existing highway or route numbers may seem to be the simplest method of assigning numbers and describing sections, it can become difficult to use. For example, a five-mile long urban highway may have several cross-sections, surfaces, and traffic volumes. Figure 4.1 is an example of a sample network using route designation. While route designations are easily recognizable and understandable, they provide little information about the individual sections of the route.

Special Codes can be developed in many ways and is particularly useful since it provides a great deal of flexibility. It can account for some of the variation found on long sections of highways. However, the disadvantage is that users have to be more familiar with the coding system in order to understand it. It could lead to poor communications. Figure 4.2 is an example of the same network using special codes as identifiers.

LINK-NODE SYSTEMS: A link-node system generally defines sections based on sections of pavement from one node (e.g. interchange, overpass, intersections or other prominent feature) to another. One example of link-node systems is superimposing a grid system over a map of the road network so that each box in the grid has a unique number as shown in Figure 4.3. Inside each box, each node is assigned a code so that the pavement section can be described by its two node points. Many agencies with urban networks use this system.

A Geographical Information System (GIS) provides another method of numbering and locating sections with the latest in computer technology. A coordinate system is used to store the network-wide map on the computer. The sections are then defined by the coordinates of the end points. Sections can be selected or identified directly on the computer screen map by pointing to the correct highway.

There are various alternative numbering systems. For example, section numbers can be assigned to block segments and intersections using existing highway numbers as shown in Figure 4.3. This system is useful because it utilizes an existing numbering system while providing a unique number assignment for intersections and other features.

Figure 4.1 Example using route designations

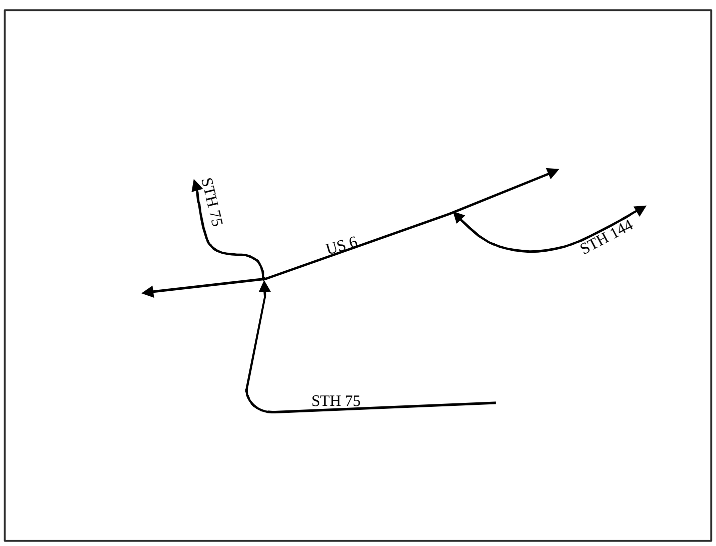


Figure 4.2 Example of special code designation

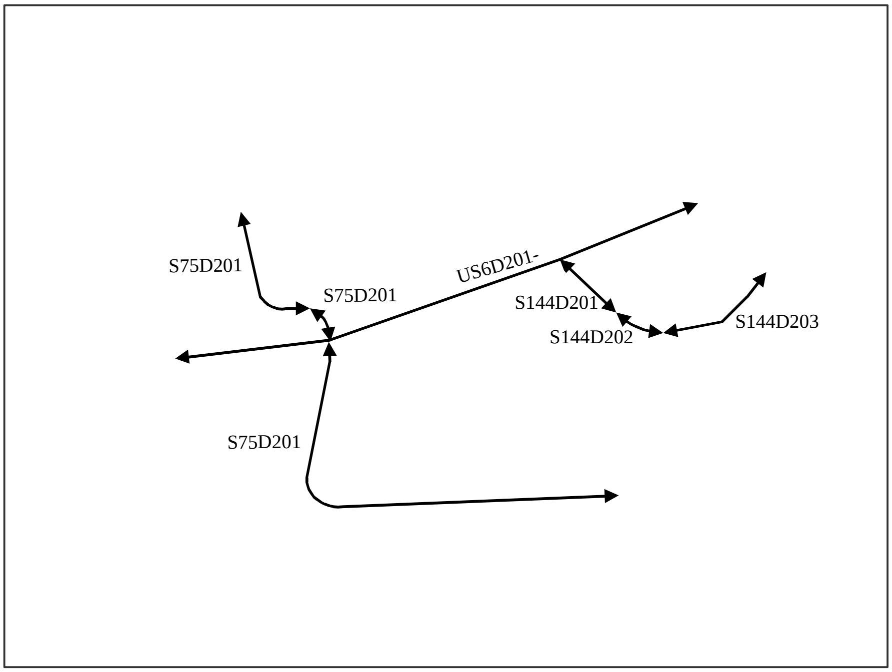
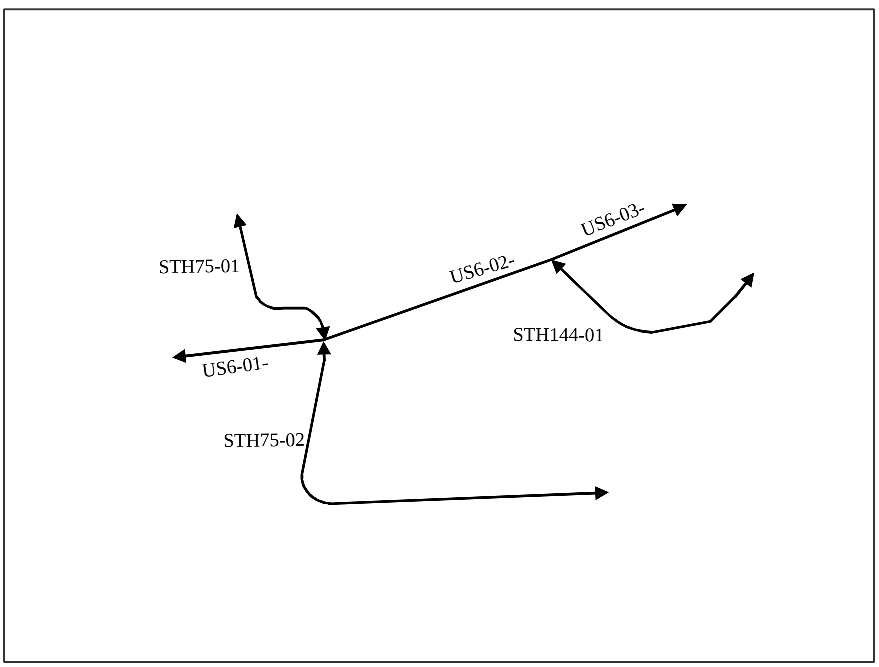


Figure 4.3 Example of link-node designation



Whatever type of procedure is selected for identifying sections, one item remains critical to each, and that is, field crews and other database systems MUST be able to locate exact section boundaries both in the field and within the databases. The more permanent the location markers are, the easier and more accurate the data collection process. If permanent markers are not available the use of an accurate distance measuring instrument (DMI) mounted on the survey vehicle can be used to locate sections. If this is the case, the surveyor(s) must know the exact section lengths and have several benchmarks from which to start measuring.

4.5 Collecting Inventory Data

There are specific basic principles when collecting inventory data. As much data as possible should be developed in the office first and prepared on data forms or tabular formats so that a field verification of the inventory can be performed efficiently. It is much more effective to verify data in the field than to try to record all of the data in the field and confirm it later. Information such as construction history can be added to the inventory later, as time and money permit.

There are several methods of collecting the necessary data in the field as discussed below.

Video or Photographic Logging: This requires more specialized equipment but field time is dramatically reduced. The records are then reviewed in the office and the data is entered into the PMS. This office review will be the largest part of the data collection process. This system also provides a permanent record of the road inventory. The video/photographic logging is limited by the view captured by the camera. Some of the equipment available to perform this video or photographic log is discussed in Module 5.

Field Surveys: Field survey crews can view and analyze a wider area along the road alignment. This method is slow and time consuming and should only be used in localized areas. The only permanent record is the notes of the field survey team. If a field survey team is to be used, experience shows that using two-person survey team(s) is more efficient and accurate. Before beginning the field work, the team(s) should receive all necessary training and have a thorough understanding of the following:

- Sections in the network
- Inventory data collection format
- Definition of sections and identification procedures
- Structure of inventory database
- Prioritized list of data to collect
- Prioritized list of roads to be verified

Maps of the pavement network should be completed before the survey team(s) begins field work and should include the following:

- Highway or road classification
- Defined section boundaries
- Route numbers or road names
- Geographic details and political boundaries

The proper equipment is essential for the survey team(s) to perform the inventory survey. Typically, this includes a vehicle equipped with a distance measuring instrument (DMI), and a manual measuring wheel. The use of a vehicle odometer is not recommended because its accuracy is questionable and 1/10-mile measurements are insufficient. Also helpful is a supply of sharpened pencils, erasers, a calculator, clipboard, safety vest (preferably with pockets), hard hat, markers (highlighting kind), a can of spray paint, keel, warning beacon, a traffic cone, and plenty of blank data forms.

Recent developments have led to the use of other equipment to assist in the collection of inventory data, such as ground penetrating radar (GPR) which is discussed below, global positioning systems (GPS) which was discussed in Module 3, and video logging vehicles which will be discussed in Module 5.

After all of the above criteria have been met, the survey team is ready to begin field data collection of inventory data. This process should be approached in the following sequence:

- Determine the area to be inventoried
- Drive along the selected route to establish section limits
- Measure and record the physical dimensions
- Make another pass through the section and complete any missing inventory data on the form, and record the section length

Traffic volumes are usually obtained through weigh-in-motion (WIM) counts or more traditional methods. This is further discussed in Module 7.

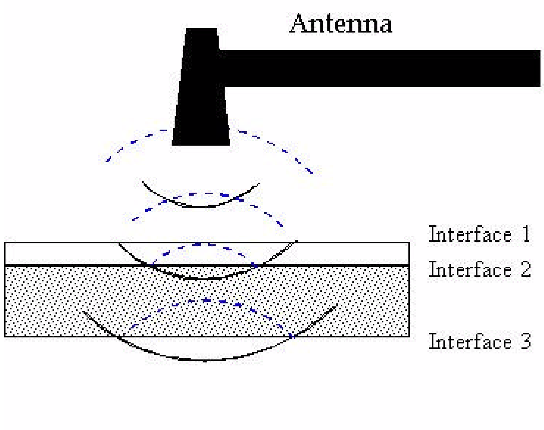
A streamlined database can be developed by using well-defined inventory and data forms. These forms are used by the survey team and office personnel to record the inventory information. These forms are permanent records and are only updated as major physical characteristic changes occur. This differs from the requirements for pavement condition inspection information, which is done at a recurring interval, and is always changing.

GROUND PENETRATING RADAR (GPR) is a nondestructive method to determine the thickness of pavement layers. The system uses the same technology as airborne and seagoing radar used throughout the world.

Radar which is a contraction of the term Radio Detecting And Ranging uses radio waves to detect objects and determine their distance (range) from the echoes they reflect. Ground Penetrating Radar was first developed by MIT to find shallow tunnels in the late 1960's during the Vietnam War. GPR has since been modified to detect anomalies in highway pavements and bridge decks.

An electronic impulse (radio signal) is emitted by an antenna. When the impulse reaches an interface between to different materials some of the energy is reflected back and this energy is picked up by another antenna. (see Figure 4.4) By knowing the travel time of the energy pulse, the distance traveled and the distance away from the energy source is calculated.

Figure 4.4 Ground penetrating radar (GPR)



The strength of the energy return is dependent on the interface between the two materials and the difference in the dielectric constant between the two materials. The dielectric constant provides a measurement of a material's ability to transmit electricity. Metals that conduct electricity well reflect most of the radio pulse. Air which is a poor conductor of electricity transmits most of the radio pulse and reflects very little. In the case of an airplane the interface is between the air and the metal of the airplane. These two materials are very different and produce a strong reflection of the radio pulse. This may not be the case when GPR is used to evaluate pavement structures. The dielectric constants of the various materials may not be that different and the interface may not be well defined. For both bound and unbound materials the relative dielectric constant is highly dependent upon the amount of free moisture in the material as well as the mineral makeup of the material. Sands and gravels are not as reflective of radio energy pulses as clays. For example the dielectric constant for aggregate base course may be very similar to a sandy soil. This may make it difficult to identify the interface between the two materials. However, the interface between aggregate base and a clay soil are more readily detected. The dielectric constants for both ACC and PCC and aggregate base course are very different and the interface can be identified much easier.

The depth of radar penetration into the ground is based upon the frequency of the radar antenna and the type of pavement layers. The lower the frequency the deeper the radar energy will penetrate into the pavement. Resolution is also dependent on the frequency of the radar antenna. Higher frequency provides better resolution.

Two basic types of GPR equipment are available. The first type is the contact type commonly referred to as ground-coupled. The antenna is place directly on the pavement surface and then a continuous reading is taken as the antenna is pulled along the ground at a walking pace. This type of equipment provides better resolution and is more commonly available. It is used for more project specific research type surveys. The other type of equipment uses horn shaped air-coupled antennas which are mounted about 250 mm above the pavement and can operate at close to normal highway speeds. The resolution of air-coupled systems is lower than ground-coupled systems but they can travel at highway speeds and are most commonly used for PMS applications because data can be collected over an entire road network much more economically. For pavement thickness surveys an air-coupled antenna is operated with center frequencies around 1 GHz which provides thickness resolution of about 10 mm (but penetration depth is limited to about 0.6 m). A GPR study by Kansas indicated that the cost of a GPR pavement survey, including data analysis and reporting, ranges from $30 to $435/lane km. The cost depended on the distance surveyed and the level of detail required for the data analysis. The lower range represented only network pavement thickness analysis while the upper range represented more project specific special studies.

The GPR technology can be applied to PMS to better determine the pavement structure and the location of where the pavement structures change. The GPR data is very applicable to project level analysis. The GPR data can provide information concerning the pavement layer thicknesses, layer variability, voids, and the location of utilities.

Data interpretation for GPR has improved considerably over the last few years. The systems are now able to display the radar traces using a spectrum of colors to identify the strength of the radar return. Large changes in signal strength indicate an interface. This technique has improved the ability of GPR to locate voids thicker than 6 mm under PCC and in some cases the presence of water in a pavement structure. The interface between free water and the subgrade soil or water in a void is very pronounced and can be readily identified using this color enhancement technique.

In the NCHRP Synthesis 255 on GPR the capabilities of current GPR systems are listed as:

> <u>Asphalt layer thickness determination</u>: GPR results are used to estimate thickness to within 10 percent and thicknesses of up to 0.5 m are accurately measured
>
> <u>Base thickness determination</u>: thicknesses are estimated, provided that there is a dielectric contrast between the base and subgrade. (The best results occur when subgrade is made up of clay soils which are highly conductive compared to sands or gravels.)
>
> <u>Concrete thickness determination</u>: depth constraints and accuracy are not yet well defined. This is because Portland cement concrete attenuates GPR signals more than asphalt, PCC conductivity changes as the cement hydrates, slabs that contain reinforcing steel make interpretation more difficult, and the dielectric contrast between the PCC and base may not be adequate for reflection detection.
>
> <u>Void detection</u>: GPR has detected air-filled voids as thin as 6 mm, while the detection of water-filled voids is more problematic.

At the present time the primary use of GPR in PMS is to provide network level information about pavement layer thickness as part of the inventory database. At the present time it has been used more by local agencies where there was no existing information on surfacing thicknesses. For this application the GPR survey is run to develop a pavement layer inventory. The more existing pavement layer information an agency has to compare against the GPR survey data the better. GPR is an anomaly detector which means that comparisons to known thickness of coring is necessary for the best validation of the data collected.

Several States, (Florida and Texas) own GPR equipment. Florida uses GPR primarily to establish pavement thicknesses. The Materials Division of the Texas Transportation Institute (TTI) has developed performance specifications and test procedures of GPR systems. They have also developed a GPR training program that has been used to help train Texas DOT personnel in the two Texas DOT Districts that own and use GPR.

4.6 Quality Control

The data collection process is only as good as the data. This means that a Quality Control process must be part of the PMS inventory plan. As the data is collected, it should be verified for :

- Integrity - whenever two different pieces of data profess to represent the same fact, they must be equal. In a typical PMS database, transposing numerical data is the most common mistake.
- Accuracy - the data values represent as close as possible the actual situation at the indicated location and time. The level of accuracy should be based on the type of analysis to be performed. Increases accuracy will also increase cost. Accuracy is most often a data collection consideration. For example, if data are sorted in the database by mile long road sections, and a section had 20,000 vehicles on one half and 10,000 on the other, the value of 15,000 vehicles would not be an accurate representation of traffic on this road section.
- Validity - the given value is correct. Data validity is generally tested by comparing the given value with a range of reasonable values for the circumstances. For example, a traffic volume of 100,000 cars per day on a two-lane highway would not be a valid figure. Checks of the data should be performed at certain stages in the data collection process to eliminate common errors such as data entry.
- Security - involves two things. First, if data being stored are confidential, you must ensure proper channels must be established and followed to restrict access to authorized personnel. Second, if the data are destroyed, backups must be available so they can be restored. To prevent or reduce the risk of destroying data, users can be restricted from accessing it or, more commonly, most user access can be limited to “read only”.

Note that the principles above are similar to those previously discussed for relational databases (Module 3).

One method of achieving this goal is to use only well-trained personnel. When planning the PMS, costs for training should be included. Keeping the database as simple and streamlined as possible will also ensure that the data collected meet the criteria previously discussed.

Data quality reviews must be performed at several stages in the data collection process. The reviews should be performed after each manipulation or reduction of the data. For example the data in the database should be compared with the raw field data to insure that the data is correct and the database accurately reflects the field conditions.

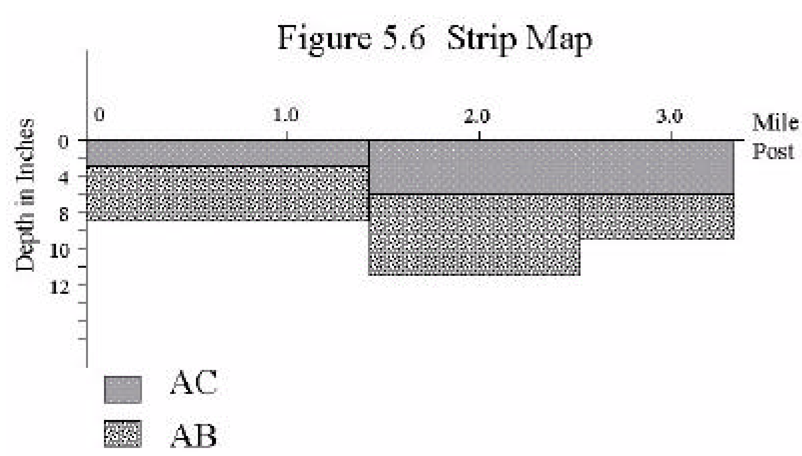
A great deal of emphasis has been placed on field data entry computer systems and their ability to reduce data entry errors. Often this process assumes that there are no data entry errors in the field. This is a faulty assumption. The same stringent quality control reviews must be performed whether the data is entered in the office or in the field. However, field data entry computers do reduce the number of times that the data is manipulated and does provide some cost savings.

4.7 Strip Maps

Strip maps are used in a PMS to represent a “picture or profile” of the inventory data for each road segment in the network. The strip map, as shown in Figure 4.6, contains basic information about a road segment. The data is displayed as a profile along the road alignment. The strip maps are very dependent on a well-established location referencing system and the ability of the data system to perform dynamic segmentation.

The contents of a strip map are only limited by the amount of data that is available. For example, data elements such as section boundaries, length, layer thicknesses, material type, lane widths, shoulder widths, traffic volume, age of pavement and treatments applied can be used. The agency should decide what data elements are important for their needs. The strip maps are an excellent way to display information to the “decision-makers” when analyzing a particular road segment. GIS systems perform a similar function using the map of the road network. It presents information in a clear, simple fashion. As the old saying goes, “A picture is worth a thousand words”.

Figure 4.5 Strip maps



It is important to note, however, that in order to develop a strip map that contains these or any other data elements, ***a logical, linear location referencing system must be in-place***. It cannot be emphasized enough, that without a solid, linear location referencing system, a PMS will probably not provide the results an agency expects.

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MODULE 5

PAVEMENT CONDITION SURVEYS

5.1 Module Objectives

The objectives of this module are to enable participants to:

- Understand the need for condition surveys.
- Be familiar with the four basic types of condition surveys.
- Acquaint participants with the different procedures and equipment available.
- Be aware of the purpose, advantage and disadvantage of different procedures.

5.2 Introduction

In the previous module, the inventory defined the network for which the pavement engineer is responsible. In this module, Condition Surveys are used to assess or describe the state of being, or readiness for use, of those elements being managed. It has also been described as a means of determining the "health" of the network.

A condition survey is the process of collecting data to determine the structural integrity, distresses, skid resistance, and overall riding quality of the pavement. Traditionally, maintenance or engineering personnel relied on experience and visual inspections to schedule maintenance. The problems with that technique are that experience is difficult to transfer from one person to another and decisions made using similar data often vary considerably. Condition surveys provide a rational and consistent method of allocating limited resources.

By monitoring the pavement condition using the methods described here, an agency should be able to:

- Evaluate the current condition of the network.
- Determine the rates of deterioration.
- Project future conditions.
- Determine maintenance and rehabilitation needs.
- Determine the costs of repair.
- Prepare plans for repairs.
- Determine the effects of budget reductions and deferred maintenance.
- Schedule future pavement maintenance activities.
- Track performance of various pavement designs and materials.

There are several methods available for defining the current condition of a pavement segment. Many of the pavement management systems (PMS) available use a specific method of collecting condition data and defining states of pavement readiness or condition. Adopting a specific PMS will often require the adoption of specific data collection procedures.

Since so many decisions supported by the PMS are based on the condition assessment, it is important to ensure that the data collected and used is accurate enough to provide the desired level of support. However, since the collection of condition data is the most expensive portion of maintaining the PMS, the cost must be matched to the resources and needs of the adopting agency.

The published literature on condition surveys is extensive and exhaustive. Much of the previously published work, as well as past NHI courses, are summarized herein. Previous PMS courses were especially useful in compiling this module. The focus of this module will be on "new" types of procedures and equipment.

5.3 Collection Methodologies

Collecting condition information is generally the most costly part of the initial implementation of a PMS and of continued operation. Condition data can be collected using very expensive or relatively inexpensive methods. In general, the detail and accuracy of data collection varies from very detailed for research activities to very gross for some network-level management systems. It is not necessary to have the same detail at each level; however, it is important to use the same general definitions at each level. It is not necessary to collect all of the data at each level. Some measures, such as structural evaluation, may only be collected at the project-level. Other measures, such as surface friction, may only be used when a specific problem has been identified.

Many different methods are available to collect each of these condition measures. The methods that are more costly are also usually more accurate, more precise, and have the greatest resolution. Accuracy is the degree to which the method provides a true value. Precision is the repeatability among multiple measurements. Resolution is the smallest increment that can be measured. The precision, accuracy, and resolution needed depend on the goals of the pavement management system and the funds available to pay for the inspection services. Some methods are more subjective than others. References *1* and *3* describe many of the data collection methods and equipment in some detail. Reference *4* discusses many of the automated or semi-automated procedures for collecting and analyzing distress data. Reference *5* presents some criteria that should be considered in selecting the data and collection methods.

5.4 Types of Surveys

Assessing the pavement condition begins with collecting data. This data is then interpreted to define the current state of readiness, or "health" of the pavement. There are generally four types of surveys *(1):*

- Distress Surveys
- Structural Capacity
- Roughness (ride quality)
- Skid Resistance (surface friction)

The basic purpose of a pavement is to provide a safe and smooth surface for the travelling public. The travelling public is primarily interested in this functional condition, which is primarily measured with roughness and surface friction. The engineers and managers are interested in developing the most cost-effective maintenance and rehabilitation program. They are interested in an engineering analysis of the condition, as well as the functional condition. Distress surveys and structural testing are normally used in the engineering analysis.

Distress Surveys: Surface distress is damage observed on the pavement surface. Distress surveys are performed to determine the type, severity, and quantity of surface distress. This information is often used to determine a pavement condition index (PCI), which helps compute a rate of deterioration, and is often used to project future condition *(2)*. Surface distress and the current or future PCI values are often used to help identify the timing of maintenance and rehabilitation as well as funding needs in the PMS process. Distress is the measure most used by maintenance personnel to determine what type of maintenance treatment is required and when maintenance is needed. It is typically the most important type of condition survey.

Structural Capacity: Structural capacity is the maximum load and number of repetitions a pavement can carry before reaching some defined condition. Structural analysis is normally conducted at the project-level to determine the pavement load-carrying capacity and the capacity needed to accommodate projected traffic. Non-destructive deflection testing of the pavement is a simple and reliable method to assist in making this evaluation; however, destructive testing such as coring and component analysis techniques may be used as well. Pavement structural evaluation is important in the selection of treatments at the project-level

Roughness (Ride Quality): Roughness, or ride quality, is a measure of pavement surface distortion along a linear plane or an estimate of the ability of the pavement to provide a comfortable ride to the users. Roughness is often converted into an index such as the Present Serviceability Index (PSI) or the International Roughness Index (IRI). Pavement roughness is considered most important by the using public, and it is especially important on pavements with higher speed limits, those above 45 miles (70 km) per hour. It is considered very important by state highway agencies, but is generally of less importance to cities because of the difference in speed limits as well as the causes of roughness.

Skid Resistance (Surface Friction): Skid resistance, or surface friction, indicates the ability of the pavement surface to provide sufficient friction to avoid skid related safety problems. Skid resistance is most important on pavements with high speeds. It is generally considered a separate measure of the condition of the pavement surface and often can be used to determine the need for remedial maintenance by itself. Many agencies use accident maps to identify high accident areas, and then an assessment is made as to whether the accidents are related to friction problems. Measurements of surface friction can be used to help eliminate potential problem spots before accidents occur.

Skid resistance measurements are expressed as a skid number. On highway pavements, skid measurements are usually made with locked wheel skid trailers. Measurement of skid resistance is not typically associated with a PMS at the local level.

Summary of Survey Types: These four pavement condition factors can be used to determine the overall pavement condition and to identify the most cost-effective and optimum maintenance and rehabilitation treatment. The pavement condition factors discussed above vary in their degree of importance in terms of pavement performance and maintenance and rehabilitation needs. It is obvious that a treatment recommended to correct the structural load-carrying capacity of the pavement can be designed to correct all other deficiencies that might be present, including roughness. Also, a treatment selected to correct pavement roughness can be used in turn to improve the surface friction and correct any surface distress as well.

Various methods are available to collect each of the four measures. Each method has advantages and disadvantages. Again, to emphasize, those procedures which require the least time and cost are also the least accurate. Those which are most accurate are also the most expensive and time consuming. An agency must carefully consider the type and level of decisions being made along with the resources available to determine the best method and correct measures for their system. There is considerable variation in the cost and accuracy of data collected. In general, most agencies use less accurate methods for network-level analysis and more detailed measures for project-level analysis. However, the network and project-level methods should complement each other.

Survey Frequencies: The frequency of surveys depends upon several factors. These include pavement type, age, current condition, average daily traffic, axle loadings, drainage characteristics, and weather factors. Of these factors, current conditions, axle loadings and drainage are the most important.

Traffic loadings are usually consistent within each road class. Therefore, if traffic and axle loading data are not readily available, it may be reasonable to assign survey frequency by functional classification. For instance, arterials might be inspected annually, collectors every two years, and residential streets every four years.

Frequency also depends on the pavement condition of individual sections. New pavements or pavements in good condition require less frequent inspections than pavements that are experiencing high rates of deterioration.

5.5 Distress Surveys

Distress surveys can be performed manually, or automated equipment may be used. In either case, the surface of the pavement is viewed and evaluation is made to determine the following:

- Type of distress.
- Severity.
- Quantity of distress present on the pavement surface.

The type of distress tells us what type of damage has developed; the severity tells how bad the damage is; and the quantity gives us the extent of the type and severity of damage that is present. All three of these factors are required to get a full picture of the damage that has developed on the pavement surface and are used to determine the type and timing of maintenance, rehabilitation, and reconstruction.

There have been several iterations in the development of standard definitions of types of distress and levels of severity. The definitions used in the PAVER system are some of the most commonly used by local agencies *(6,7);* however, they are often criticized because there are too many distress types required by PAVER (19 each for asphalt and concrete surfaced pavements, 7 for unsurfaced roads). Since PAVER was developed for worldwide use, a full set of distress types were needed. However, in a single area, fewer distress types will normally be present and even less may influence management decisions. Some agencies have modified the PAVER distress types and severity levels to make them more easy to use and to match the conditions found in a local area *(8).* One such example is the Metropolitan Transportation Commission's PMS in California.

Distress severity levels have also evolved. Some state agencies and the Federal Highway Administration using the Strategic Highway Research Program (SHRP) Distress Identification Manual for Long-Term Pavement Performance *(9)* have tried to avoid using severity levels and rely on direct measures to define the severity and reduce subjectivity. (See Table 5.1). This is appropriate for such distress types as rutting where direct depth measurements can be made. However, most agencies are still using distress severities, and even the SHRP manual uses severity levels for some distress types. The number of severity levels has varied among distress identification systems from two to seven. Most agencies currently use three. Generally, the low severity level identifies that the distress type has appeared but that it is not causing a problem at this point. A high or heavy severity level generally indicates that the distress is so bad that maintenance is needed immediately or should have already been performed.

The medium or moderate severity level generally indicates that the distress has progressed to the point where the pavement needs attention or it will become a problem shortly. This provides adequate information to define the level of damage that is present and to help identify when treatments should be applied. It also gives adequate information needed to calculate a condition index that can be used to project future condition.

In summary, a good pavement distress survey will collect data necessary to:

- Identify roads which need no immediate maintenance and therefore, no immediate expenditures.
- Identify roads which require a minor or routine maintenance and immediate expenditures.
- Identify roads which require preventive maintenance activities such as asphalt overlay, seal, etc. These roads can be listed in order of priority and the maintenance activities can be scheduled accordingly.
- Identify roads which need major rehabilitation or reconstruction. These roads will have deteriorated to the point that maintenance is no longer cost-effective and more major work is required to raise the condition to an acceptable level.

Appendix 5A is an example of the state of New Mexico's distress definitions and procedures.

Table 5.1 Distress Types from SHRP *(9)*

ASPHALT CONCRETE SURFACES	
1. Fatigue Cracking	9. Rutting
2. Block Cracking	10. Shoving
3. Edge Cracking	11. Bleeding
4. Longitudinal Cracking	12. Polished Aggregate
5. Reflection-Cracking At Joints	13. Raveling
6. Transverse Cracking	14. Lane-to-shoulder drop-off
7. Patch/Patch Deterioration	15. Water Bleeding & Pumping
8. Potholes	
JOINTED PORTLAND CEMENT CONCRETE SURFACES	
1. Corner Breaks	9. Polished Aggregate
2. Durability Cracking	10. Popouts
3. Longitudinal Cracking	11. Blow-ups
4. Transverse Cracking Joints/Cracks	12. Faulting of Transverse
5. Joint Seal Damage	13. Lane-to-shoulder drop-off
6. Spalling of Longitudinal Joints	14. Lane-to-shoulder separation
7. Spalling of Transverse Joints	15. Patch/Patch Deterioration
8. Map Cracking & Scaling	16. Water Bleeding & Pumping
CONTINUOUSLY REINFORCED CONCRETE SURFACES	
1. Durability Cracking	9. Lane-to-shoulder drop-off
2. Longitudinal Cracking	10. Lane-to-shoulder separation
3. Transverse Cracking	11. Patch/Patch Deterioration
4. Map Cracking & Scaling	12. Punchouts
5. Polished Aggregate	13. Spalling of Longitudinal Joints
6. Popouts	14. Water Bleeding & Pumping
7. Blowups	15. Longitudinal Joint Seal Damage
8. Transverse Construction Joint Deterioration	

Tables 5.2 and 5.3 are the SHRP descriptions for distress types found in asphalt and Portland cement concrete pavements.

TABLE 5.2 Distress Definitions for Asphalt Surfaced Pavements *(9)*

DISTRESS TYPE	DESCRIPTION
Bleeding	Excess bituminous binder occurring on the pavement surface. May create a shiny, glass-like, reflective surface that may be tacky to the touch. Usually found in the wheel paths.
Block Cracking	A pattern of cracks that divides the pavement into approximately rectangular pieces. Rectangular blocks range in size from approximately 0.1 sq. m to 10 sq. m (1 sq. ft to 100 sq ft).
Edge Cracking	Applies only to pavements with unpaved shoulders. Crescent shaped cracks or fairly continuous cracks which intersect the pavement edge and are located within 0.6 m (2 ft) of the pavement edge, adjacent to the shoulder. Includes longitudinal cracks outside of the wheel path and within 0.6 m (2 ft) of the pavement edge.
Fatigue Cracking	Occurs in areas subjected to repeated traffic loadings (wheel paths). Can be a series of interconnected cracks in early stages of development. Develops into many-sided, sharp-angled pieces, usually less than 0.3 m (1 ft) on the longest side characteristically with a chicken wire/alligator pattern, in later stages. Must have a quantifiable area.
Lane-to-shoulder drop-off	Difference in elevation between the traveled surface and the outside shoulder. Typically occurs when the outside shoulder settles as a result of pavement layer material differences.
Longitudinal Cracking	Cracks predominantly parallel to pavement centerline. Location within the lane (wheel path versus non-wheel path) is significant.
Patch/Patch Deterioration	Portion of pavement surface, greater than 0.1 sq. m (1 sq. ft), that has been removed and replaced or additional material applied to the pavement after original construction.
Polished Aggregate	Surface binder worn away to expose coarse aggregate.
Potholes	Bowl-shaped holes of various sizes in the pavement surface. Minimum plan dimension is 15 cm (6 in).
Raveling	Wearing away of the pavement surface in high-quality hot mix asphalt concrete. Caused by the dislodging of aggregate particles and loss of asphalt binder.
Reflection Cracking At Joints	Cracks in asphalt concrete overlay surfaces that occur over joints in concrete pavements. Note: Knowing the slab dimensions beneath the asphalt concrete surface helps to identify reflection cracks at joints.
Rutting	A rut is a longitudinal surface depression in the wheel path. It may have associated transverse displacement.
Shoving	Shoving is a longitudinal displacement of a localized area of the pavement surface. It is generally caused by braking or accelerating vehicles, and is usually located on hills or curves, or at intersections. It also may have associated vertical displacement.
Transverse Cracking	Cracks that are predominantly perpendicular to pavement centerline, and are not located over Portland cement concrete joints.
Water Bleeding and Pumping	Seeping or ejection of water from beneath the pavement through cracks. In some cases, detectable by deposits of fine material left on the pavement surface which were eroded (pumped) from the support layers and have stained the surface.

TABLE 5.3 Distress Description For Portland Cement Concrete Surfaces *(9)*

DISTRESS TYPE	DESCRIPTION
Blowups	Localized upward movement of the pavement surface at transverse joints or cracks, often accompanied by shattering of the concrete in that area.
Corner Breaks	A portion of the slab separated by a crack, which intersects the adjacent transverse and longitudinal joints, describing approximately a 45 degree angle with the direction of traffic. The length of the sides is from 0.3 m (1 ft) to one-half the width of the slab, on each side of the corner. Closely spaced crescent-shaped hairline cracking pattern. Occurs adjacent to joints, cracks, or free edges; initiating in slab corners.
Durability Cracking (“D” Cracking)	Closely spaced crescent-shaped hairline cracking pattern. Occurs adjacent to joints, cracks, or free edges; initiating in slab corners.. Dark coloring of the cracking pattern and surrounding area.
Faulting of Transverse Joints and Cracks	Difference in elevation across a joint or crack.
Joint Seal Damage	Joint seal damage is any condition which enables incompressible materials or a significant amount of water to infiltrate the joint from the surface. Typical types of joint seal damage are: Extrusion, hardening, adhesive failure (bonding), cohesive failure (splitting), or complete loss of sealant. Intrusion of foreign material in the joint. Weed growth in the joint.
Lane-to-shoulder drop-off	Difference in elevation between the edge of slab and outside shoulder; typically occurs when the outside shoulder settles.
Lane-to-shoulder separation	Widening of the joint between the edge of the slab and the shoulder.
Longitudinal Cracking	Cracks that are predominantly parallel to the pavement centerline.
Map Cracking	A series of cracks that extend only into the upper surface of the slab. Frequently, larger cracks are oriented in the longitudinal direction of the pavement and are interconnected by finer transverse or random cracks.
Scaling	Scaling is the deterioration of the upper concrete slab surface, normally 3 mm (0.125 in.) to (0.5 in.), and may occur anywhere over the pavement.
Patch/Patch Deterioration	A portion, greater than 0.1 sq. m (1 sq. ft), or all of the original concrete slab that has been removed or replaced, or additional material applied to the pavement after original construction.
Polished Aggregate	Surface mortar and texturing worn away to expose coarse aggregate.
Popouts	Small pieces of pavement broken loose from the surface, normally ranging in diameter from 25 mm (1 in.) to 100 mm (4 in.) and depth from 13 mm (0.5 in.) to 50 mm (2 in.).
Spalling of Longitudinal Joints	Cracking, breaking, chipping or fraying of slab edges within 0.6 m (2ft) of the longitudinal joint.
Spalling of Transverse Joints	Cracking, breaking, chipping or fraying of Lac edges within 0.6 m (2ft) of the transverse joint.
Transverse Cracking	Cracks that are predominantly perpendicular to the pavement centerline..
Water Bleeding and Pumping	Seeping or ejection of water from beneath the pavement through cracks. In some cases detectable by deposits of fine material left on the pavement surface, which were eroded (pumped) from the support layers and have sustained the surface.
Transverse Construction Joint Deterioration	Series of closely spaced transverse cracks or a larger number of interconnecting cracks occurring near the construction joint.
Punchouts (CRCP only)	The area enclosed by two closely spaced (usually less than 0.6 m [2ft]) transverse cracks, a short longitudinal crack, and the edge of the pavement or a longitudinal joint. Also includes ”Y” cracks that exhibit spalling, breakup, and faulting.

Tables 5.4 and 5.5 are descriptions of distress types found in aggregate-surfaced and brick, block or cobblestone pavements, respectively.

Table 5.4 Distress Types for Aggregate Surfaced Pavements *(10)*

DISTRESS TYPE	DESCRIPTION
Corrugations	Corrugations (also known as washboarding) are closely spaced ridges and valleys (ripples) at fairly regular intervals. The ridges are perpendicular to the traffic direction. This type of distress is usually caused by traffic and loose aggregate. These ridges usually form on hills, on curves, in areas of acceleration or deceleration, or in areas where the road is soft or potholed.
Dust Generation	The wear and tear of traffic on unsurfaced roads will eventually loosen the larger particles from the soil binder. As traffic passes, dust clouds create a danger to trailing or passing vehicles and cause significant environmental problems.
Improper Cross Section	An unsurfaced road should have a crown with enough slope from the centerline to the shoulder to drain all water from the road's surface. No crown is used on curves, because they are usually banked. The cross section is improper when the road surface is not shaped or maintained to carry water to the ditches.
Inadequate Roadside Drainage	Poor drainage causes water to pond. Drainage becomes a problem when ditches and culverts are not in good enough condition to direct and carry runoff water because of improper shape or maintenance.
Loose Aggregate	The wear and tear of traffic on unsurfaced roads will eventually loosen the larger aggregate particles from the soil binder. This leads to loose aggregate particles on the road surface or shoulder. Traffic moves loose aggregate particles away from the normal road wheel path and forms berms in the center or along the shoulder (the less-traveled areas).
Potholes	Potholes are bowl-shaped depressions in the road surface. They are usually less than 3 feet in diameter. Potholes are produced when traffic wears away small pieces of the road surface. They grow faster when water collects inside the hole. The road then continues to disintegrate because of loosening surface material or weak spots in the underlying soils.
Ruts	A rut is a surface depression in the wheel path that is parallel to the road centerline. Ruts are caused by a permanent deformation in any of the road layers or subgrade. They result from repeated vehicle passes, especially when the road is soft. Significant rutting can destroy a road.

Table 5.5 Distress Types for Brick, Block or Cobblestone Pavements (10)

Distress Type	Description
Displacement	Localized surface areas with horizontally displaced brick or block caused by slipping or shoving of the base material.
Heaving	Bumps caused by frost heave, swelling soils, or displacement of base material.
Pothole	Depressions in the pavement surface resulting from loss of brick or block.
Rutting	Surface depressions in the wheel path.
Settlement	Difference in elevation across joints between paving blocks or bricks; usually due to consolidation or loss of the subgrade soil.

AASHTO Distress Survey Protocols: Continuous work is being performed to standardize the definitions and procedures for collection of pavement surface distresses nationwide. NHI is currently offering a course on the SHRP Distress Identification Manual *(9)* where the emphasis is on standardizing distress definitions. The SHRP manual considers distress type of asphalt concrete, jointed Portland cement concrete and continuously reinforced Portland cement concrete pavements. A 1994 survey (27) found the widest variation among states in the collection and use of pavement distress information. There is little evidence of standardization, and the report encourages the incorporation of SHRP methods to facilitate the exchange of pavement condition information.

In addition, the FHWA is in the process of developing data collection protocols for pavement distresses. A final draft was completed in October 1996 and distributed to the states for comments. The protocols were developed with the input for 5 states (Georgia, Pennsylvania, Massachusetts, Kentucky, and South Dakota) as well as AASHTO and the American Society for Testing Methods (ASTM).

The protocols include the following:

- Cracking protocols for asphalt pavements
- Cracking protocols on jointed concrete pavements
- Cracking protocols for continuously reinforced concrete pavements
- Faulting protocols for concrete pavements
- Rut depth protocols for asphalt pavements
- Roughness protocols

Each protocol contains a definition of the distress type, the three severity levels and the procedure for rating using both manual and automated surveys. In addition, a section on quality assurance is included.

It is anticipated that the final protocols will be published in 1997 and be included in the American Association of State Highway & Transportation Officials' (AASHTO) new guide for pavement management (expected to be completed in 1998 or 1999). Appendix 5B contains the final draft (dated October 1996) of the so-called AASHTO protocols.

Manual Distress Surveys: Manual distress collection can vary from a detailed walking survey to a riding survey at 50 miles (80 km) per hour. In general, the methods in use include the following:

1. A detailed walking survey of 100% of the pavement surface in which all distress types, severities, and quantities are measured, recorded, and *mapped;*
2. A detailed walking survey of 100% of the pavement surface in which all distress types, severities, and quantities are measured and recorded;
3. A walking survey of a *sample* of the pavement surface in which all distress types, severities, and quantities within the sample areas are measured and recorded;
4. A walking survey of a *sample* of the pavement surface in which all distress types, severities, and quantities within the sample areas are *estimated* and recorded;
5. A windshield survey in which distress types, severities and quantities are estimated while riding on the shoulder at a slow speed with periodic stops where selected distress types, severities, and quantities within the selected area are estimated and recorded while walking;
6. A windshield survey at normal traffic speeds in which some distress types, severities, and quantities are estimated while riding with periodic stops where distress types, severities, and quantities within the selected area are estimated and recorded while walking or standing along the edge of the pavement surface;
7. A windshield survey in which distress types, severities, and quantities are estimated and recorded while riding on the shoulder at a slow speed;
8. A windshield survey in *normal traffic* in which distress types, severities, and quantities are estimated and recorded; and
9. A windshield survey at normal traffic speed in which the rater gives the pavement a general category or sufficiency rating without identifying individual distress types.

In general, the cost, accuracy, precision, and resolution decreases from 1 to 9 while the subjectivity increases. However, as long as people are performing the surveys, there is no way to completely eliminate subjectivity from the process. The same definitions of distress types and severities can be used for each method; however, the ability to identify lower severity levels decreases from 1 to 8. In addition, fewer distress types are able to be identified and recorded as the speed of travel increases. In many riding surveys, only the higher severities are included and relatively few distress types are collected. The same methods of defining quantities can also be used; however, the accuracy of quantity estimates decreases from 1 to 8. In general, when riding surveys are used, the raters are often required only to identify categories of quantities, such as 1 to 5%, 6 to 15%, etc., rather than estimate actual quantities. The sufficiency rating procedure described in *9* is generally not considered acceptable for pavement management purposes. NCHRP (27) reports that a total of 40 states still use a manual survey. Only 8 use automated procedures.

Recording Distress Data: In any of the collection measures, many different methods of recording the data are available. In general, the distress data can be recorded on paper forms for later entry into the database, or the data can be entered into a portable computer. The portable computer must be hand held for walking surveys. It can be mounted in the vehicle for riding surveys. The data can be entered through a standard terminal keyboard or through a special keyboard on which distress types and severities have special keys. The data in the computers can then be transferred to the database electronically. The latest innovation is the use of electronic clipboards in which the rater writes or makes checks on the screen. Recording the data on computers decreases data entry errors because it is recorded only once; however, the agency must purchase the computers and buy, or program, the data entry programs. Reference *11* describes many different data recording procedures.

The following examples illustrate sample data collection sheets for mapping and recording distress data for the SHRP procedure *(9)*.

Figure 5.1 Sample Data Collection Sheets

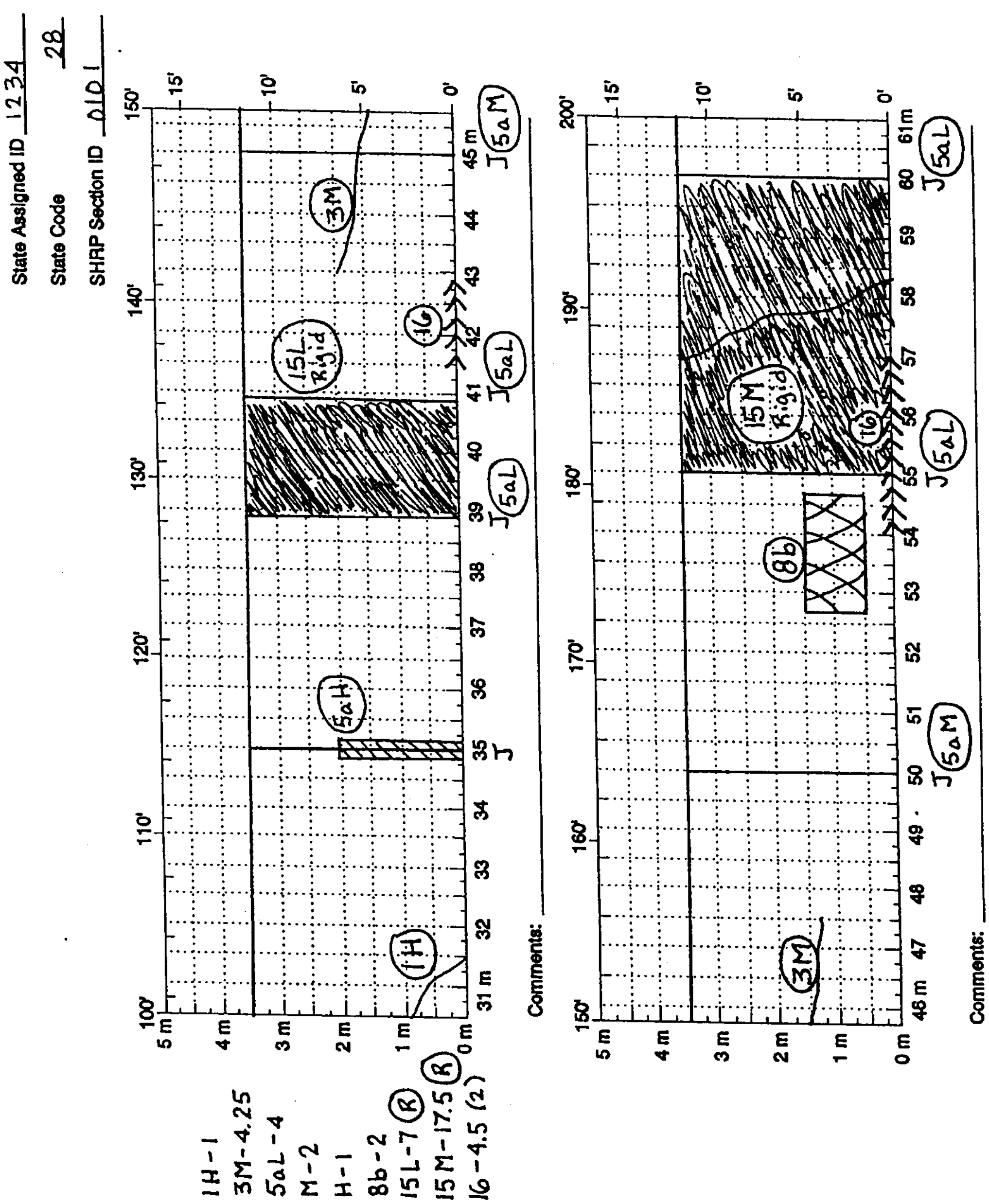


Figure 5.1 Sample Data Collection Sheets, cont.

Revised May 29, 1992

SHEET 4

DISTRESS SURVEY

LTPP PROGRAM

STATE ASSIGNED ID 1 2 3 4

STATE CODE 2 8

SHRP SECTION ID Ø 1 Ø 1

DISTRESS SURVEY FOR PAVEMENTS WITH JOINTED PORTLAND CEMENT CONCRETE SURFACES

DATE OF DISTRESS SURVEY (MONTH/DAY/YEAR) Ø6/12/92

SURVEYORS: J S R, E J F, _ _ _

PAVEMENT SURFACE TEMP - BEFORE _ _ 18 °C; AFTER _ _ 19 °C

PHOTOS, VIDEO, OR BOTH WITH SURVEY (P, V, B) P

DISTRESS TYPE	SEVERITY LEVEL LOW	MODERATE	HIGH
CRACKING			
1. CORNER BREAKS (Number)	1	Ø	3
2. DURABILITY "D" CRACKING (Number of Affected Slabs)	Ø	Ø	Ø
AREA AFFECTED (Square Meters)	Ø.Ø	Ø.Ø	Ø.Ø
3. LONGITUDINAL CRACKING (Meters)	4.8	9.2	Ø.Ø
Length Sealed (Meters)	Ø.Ø	Ø.Ø	Ø.Ø
4. TRANSVERSE CRACKING (Number of Cracks)	1	1	Ø
(Meters)	1.8	3.5	Ø.Ø
Length Sealed (Meters)	Ø.Ø	3.5	Ø.Ø
JOINT DEFICIENCIES			
5a. TRANSVERSE JOINT SEAL DAMAGE Sealed? (Y, N)			Y
If "Y" Number of Joints	8	4	2
5b. LONGITUDINAL JOINT SEAL DAMAGE Number of Longitudinal Joints that have been sealed (0, 1, or 2)			2
Length of Damaged Sealant (Meters)			4.Ø
6. SPALLING OF LONGITUDINAL JOINTS (Meters)	Ø.Ø	Ø.Ø	Ø.Ø
7. SPALLING OF TRANSVERSE JOINTS Number of Affected Joints	Ø	Ø	Ø
Length Spalled (Meters)	Ø.Ø	Ø.Ø	Ø.Ø

Figure 5.1 Sample Data Collection Sheets, cont.

Revised May 29, 1992

SHEET 5

DISTRESS SURVEY

LTPP PROGRAM

STATE ASSIGNED ID 1 2 3 4

STATE CODE 2 8

SHRP SECTION ID ∅ 1 ∅ 1

DATE OF DISTRESS SURVEY (MONTH/DAY/YEAR) ∅ 6/1 2/9 2
SURVEYORS: J S R, E J F

DISTRESS SURVEY FOR PAVEMENTS WITH JOINTED
PORTLAND CEMENT CONCRETE SURFACES
(CONTINUED)

DISTRESS TYPE	SEVERITY LEVEL LOW	MODERATE	HIGH
SURFACE DEFORMATION			
8a. MAP CRACKING (Number)			∅
(Square Meters)			∅.∅
8b. SCALING (Number)			1
(Square Meters)			2.∅
9. POLISHED AGGREGATE (Square Meters)			∅.∅
10. POPOUTS (Number per Square Meter)			∅
MISCELLANEOUS DISTRESSES			
11. BLOWUPS (Number)			∅
12. FAULTING OF TRANSVERSE JOINTS AND CRACKS - REFER TO SHEET 6			
13. LANE-TO-SHOULDER DROPOFF - REFER TO SHEET 7			
14. LANE-TO-SHOULDER SEPARATION - REFER TO SHEET 7			
15. PATCH/PATCH DETERIORATION			
Flexible			
(Number)	∅	∅	∅
(Square Meters)	∅.∅	∅.∅	∅.∅
Rigid			
(Number)	1	2	∅
(Square Meters)	7.∅	21.3	∅.∅
16. WATER BLEEDING AND PUMPING (Number of Occurrences)			2
Length Affected (Meters)			4.5
17. OTHER (Describe)			

Figure 5.1 Sample Data Collection Sheets, cont.

Revised April 23, 1993

SHEET 6

DISTRESS SURVEY

LTPP PROGRAM

STATE ASSIGNED ID 1 2 3 4

STATE CODE 2 8

SHRP SECTION ID Ø 1 Ø 1

DATE OF DISTRESS SURVEY (MONTH/DAY/YEAR) Ø 6/1 2/9 2

SURVEYORS: J S R, E J F

DISTRESS SURVEY FOR PAVEMENTS WITH JOINTED PORTLAND CEMENT CONCRETE SURFACES (CONTINUED)

12. FAULTING OF TRANSVERSE JOINTS AND CRACKS

Page 1 of 1

Point[1] Distance (Meters)	Joint or Crack (J/C)	Crack Length (Meters)	Well Sealed (Y/N)	Length of Joint Spalling, m: L	M	H	Faulting[2], mm: 0.3m	0.75m
Ø.1	J			Ø.	Ø.	Ø.	Ø	Ø
5.Ø	J			Ø.	Ø.	Ø.	3	4
1Ø.Ø	J			Ø.	Ø.	Ø.	2	3
12.3	C	3.5	Y				2	1
15.Ø	J			Ø.	Ø.	Ø.	1	2
2Ø.Ø	J			Ø.	Ø.	Ø.	4	5
25.Ø	J			Ø.	Ø.	Ø.	3	2
3Ø.Ø	J			Ø.	Ø.	Ø.	1	Ø
35.Ø	J			Ø.	Ø.	Ø.	1	Ø
38.8	J			Ø.	Ø.	Ø.	5	-4
4Ø.8	J			Ø.	Ø.	Ø.	3	-4
45.Ø	J			Ø.	Ø.	Ø.	2	3
5Ø.Ø	J			Ø.	Ø.	Ø.	1	Ø
55.Ø	J			Ø.	Ø.	Ø.	1	Ø
6Ø.Ø	J			Ø.	Ø.	Ø.	Ø	1

Note 1. Point Distance is from the start of the test section to the measurement location.

Note 2. If the "approach" slab is higher than the "departure" slab, faulting is recorded as positive (+ or 0); if the "approach" slab is lower, record faulting as negative (-) and the minus sign must be used.

Figure 5.1 Sample Data Collection Sheets, cont.

Revised May 29, 1992

SHEET 7	STATE ASSIGNED ID 1 2 3 4
DISTRESS SURVEY	STATE CODE 2 8
LTPP PROGRAM	SHRP SECTION ID Ø 1 Ø 1

DATE OF DISTRESS SURVEY (MONTH/DAY/YEAR) Ø 6/1 2/9 2
SURVEYORS: J S R, E J E

DISTRESS SURVEY FOR PAVEMENTS WITH JOINTED PORTLAND CEMENT CONCRETE SURFACES (CONTINUED)

13. LANE-TO-SHOULDER DROPOFF

14. LANE-TO-SHOULDER SEPARATION

Point No.	Point[1] Distance (meters)	Lane-to-shoulder[2] Dropoff (mm)	Lane-to-shoulder Separation (mm)	Well Sealed (Y/N)
1.	0.	_ _ 4.	_ _ 8.	Y
2.	15.25	_ _ 8.	_ _ 6.	Y
3.	30.5	_ _ Ø.	_ 1 Ø.	Y
4.	45.75	_ _ 6.	_ _ 8.	Y
5.	61.	_ _ _.	_ _ _.	_
6.	76.25	_ _ _.	_ _ _.	_
7.	91.5	_ _ _.	_ _ _.	_
8.	106.75	_ _ _.	_ _ _.	_
9.	122.	_ _ _.	_ _ _.	_
10.	137.25	_ _ _.	_ _ _.	_
11.	152.5	_ _ _.	_ _ _.	_

NOT MAPPED

Note 1. Point Distance is from the start of the test section to the measurement location. The values shown are SI equivalents of the 50 ft spacing used in previous surveys.

Note 2. If heave of the shoulder occurs (upward movement), record as a negative (-) value. Do not record (+) signs, positive values are assumed.

Yet another procedure for collecting data was developed by the Texas Innovation Group and distributed by the U.S. Department of Transportation's Technology Sharing Program *(12).*

This survey includes both a data form for recording type, severity, and extent of distress, and a scoring key for determining distress points for each distress type.

Figure 5.2 is a completed sample data form for flexible pavements. The steps required to complete the data form are:

1. Identify the distress type
2. Determine the degree (severity) of distress
3. Estimate the percentage of area affected

The distress type and severity should be determined using the standard definitions and photographs included in the manual. When the distress type and severity have been determined, the percentage of area is estimated as one of the ranges shown.

Once the distress data form has been completed, distress points are assigned to each distress type. This is done using the scoring key shown in Figure 5.3. For example, on the completed form in Figure 5.2, rutting was noted as slight and occurring on less than 15 percent of the area. From the scoring key, the distress points for this condition equal 0.

For both longitudinal and transverse cracking, the score depends on whether the cracks are sealed, partially sealed, or not sealed. The overall score for the segment is the sum of all its scores for individual defects.

The total distress points indicate the condition of one section relative to others. A higher distress point total indicates a poorer pavement. The Training Manual suggests maintenance action for any segment with a score above 10, and reconstruction of any segment with a score above 50. Your county may choose different cutoff scores.

The advantages of this method include:

- Distress type, severity, and area are accounted for.
- Visual inspections are used instead of detailed measurements.
- It may be used for any size network.
- Scoring key provides emphasis for more important distress types.

Some disadvantages are:

- The rating scale is not 0 to 100.
- Maintenance categories are very broad.
- Priorities are difficult to establish.

Figure 5.2 Inventory Data Form *(12)*

INVENTORY DATA FORM A
(Flexible Pavement)

Street Name Shakespeare Section No. 9

From Romeo To Juliet

Types of Distress	Degree of Distress	Percentage of Area			
		1-15%	16-30%	31%-	
RUTTING	Slight	✓			
0 Score	Moderate				
	Severe				
RAVELING	Slight				
12 Score	Moderate		✓		
	Severe				
FLUSHING	Slight	✓			
5 Score	Moderate				
	Severe				
CORRUGATIONS	Slight				
12 Score	Moderate		✓		
	Severe				
ALLIGATOR CRACKING	Slight				
	Moderate				
15 Score	Severe	✓			
TRANSVERSE CRACKING	Slight		✓		Check One:
	Moderate				Sealed __
7 Score	Severe				Partially Sealed ✓
					Not Sealed __
LONGITUDINAL CRACKING	Slight				Check One:
10 Score	Moderate	✓			Sealed __
	Severe				Partially Sealed __
					Not Sealed ✓
PATCHING	Slight				
5 Score	Moderate	✓			
	Severe				

66
Total
Distress Points

Figure 5.3 Scoring Key – Flexible Pavement *(12)*

SCORING KEY A
(Flexible Pavement)

Street Name Shakespeare Section No. 9
From Romeo To Juliet

Types of Distress	Degree of Distress	Percentage of Area		
		1-15%	16-30%	31%-
RUTTING	Slight	0	2	5
	Moderate	5	7	10
	Severe	10	12	15
RAVELING	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
FLUSHING	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
CORRUGATIONS	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
ALLIGATOR CRACKING	Slight	5	10	15
	Moderate	10	15	20
	Severe	15	20	25

Types of Distress	Degree of Distress	S	PS	NS	S	PS	NS	S	PS	NS
TRANSVERSE CRACKING	Slight	2	5	8	3	7	10	3	7	12
	Moderate	5	8	10	7	10	15	7	13	15
	Severe	8	10	15	10	15	20	12	15	20

Types of Distress	Degree of Distress	S	PS	NS	S	PS	NS	S	PS	NS
LONGITUDINAL CRACKING	Slight	2	5	8	3	7	10	3	7	12
	Moderate	5	8	10	7	10	15	7	13	15
	Severe	8	10	15	10	15	20	12	15	20

Types of Distress	Degree of Distress	1-15%	16-30%	31%-
PATCHING	Slight	0	2	5
	Moderate	5	7	10
	Severe	7	15	20

S = Sealed
PS = Partially Sealed
NS = Not Sealed

SAMPLE

As was mentioned earlier, PAVER is another common distress survey procedure. PAVER is a maintenance management system developed by the U.S. Army Corps of Engineers for use on military bases. The American Public Works Association (APWA) Research Foundation offers the PAVER system complete with computer service.

The PAVER condition rating *(2)* is based on a pavement condition index (PCI) which is a scale from 0 to 100 that measures both the structural integrity and surface condition.

The pavement section must first be divided into samples. All samples may be inspected, or a smaller number of random samples may be chosen to represent the entire section. Statistical methods are used to determine the number of samples required.

Figure 5.4 shows a completed data sheet for concrete pavements. One data sheet is required for each sample unit.

The inspector completes the data form by walking over each sample unit and recording the measured distresses. A sketch is made of the sample unit using the preprinted dots which represent joint intersections. The appropriate number for each distress found in the slab is entered in the square representing the slab. The distress is also noted as low, medium, or high severity.

A portion of the inspection sheet is used to summarize the distress and severity levels found in each sample unit. The PCI is calculated using the following steps:

1. The deduct values are determined for each distress type and severity using deduct valve curves. For example, the deduct value curve for distress No. 22, corner break, is shown in Figure 5.4. The deduct value is determined by entering the graphs at the distress density percent, which is 5, found opposite distress type 22 in the “% Slabs” column of the completed inspection sheet. Following the 5 percent line upward, it can be seen that it intersects the medium severity (M) curve at the deduct value of 8. Deduct values for all distresses are determined using the appropriate curves.

2. The total deduct value (TDV) is computed by summing all individual deduct values. The TDV is 29 in this example.

3. Once the TDV is computed, a corrected deduct value (CDV) must be determined using correction curves. The correction curve for jointed concrete pavement is shown in Figure 5.5. Notice the note that “q = number of deducts greater than 5 points.” The completed inspection sheet shows two distresses, No. 22M and No.28M, with deduct values greater than 5. The CDV is determined by entering the graph at TDV = 29 and moving upward to the intersection of the q = 2 curve. This corresponds to the CDV value of 24 as shown on the completed sample.

4. The PCI is 100-24 or 76.

Figure 5.4 Completed Jointed Concrete Sample Unit Inspection Sheet *(2)*

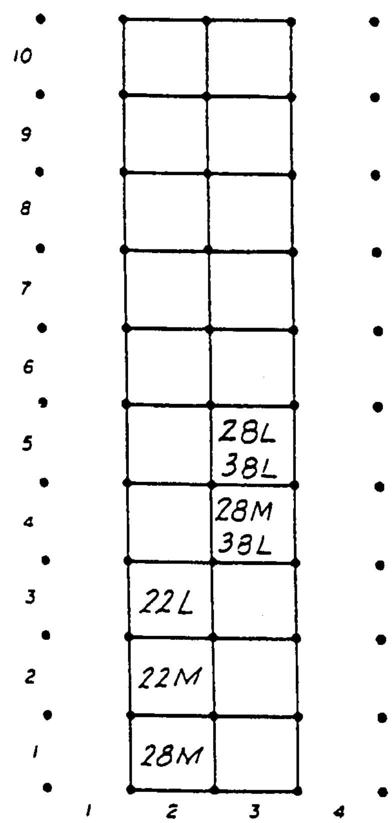
FORM A

CONCRETE PAVEMENT INSPECTION SHEET

BRANCH MARSHALL AVE. SECTION 1

DATE 10/3/79 SAMPLE UNIT 1

SURVEYED BY SK SLAB SIZE 15 x 20



Distress Types

21. Blow-Up Buckling/Shattering
22. Corner Break
23. Divided Slab
24. Durability ("D") Cracking
25. Faulting
26. Joint Seal Damage
27. Lane/Shldr Drop Off
28. Linear Cracking
29. Patching, Large & Util Cuts
30. Patching, Small
31. Polished Aggregate
32. Popouts
33. Pumping
34. Punchout
35. Railroad Crossing
36. Scaling/Map Cracking/Crazing
37. Shrinkage Cracks
38. Spalling, Corner
39. Spalling, U Joint

DIST. TYPE	SEV.	NO.** SLABS	% SLABS	DEDUCT VALUE
26*	M			4
22	L	1	5	4
22	M	1	5	8
28	L	1	5	3
28	M	2	10	9
38	L	2	10	1
DEDUCT TOTAL q = 2				29
CORRECTED DEDUCT VALUE (CDV)				24

PCI = 100 - CDV = 76

RATING = VERY GOOD

* All Distresses Are Counted On A Slab-By-Slab Basis Except Distress 26, Which Is Rated For the Entire Sample Unit.

** Total Number of Slabs Containing Each Distress of Same Severity

Figure 5.5 Deduct Value Curve

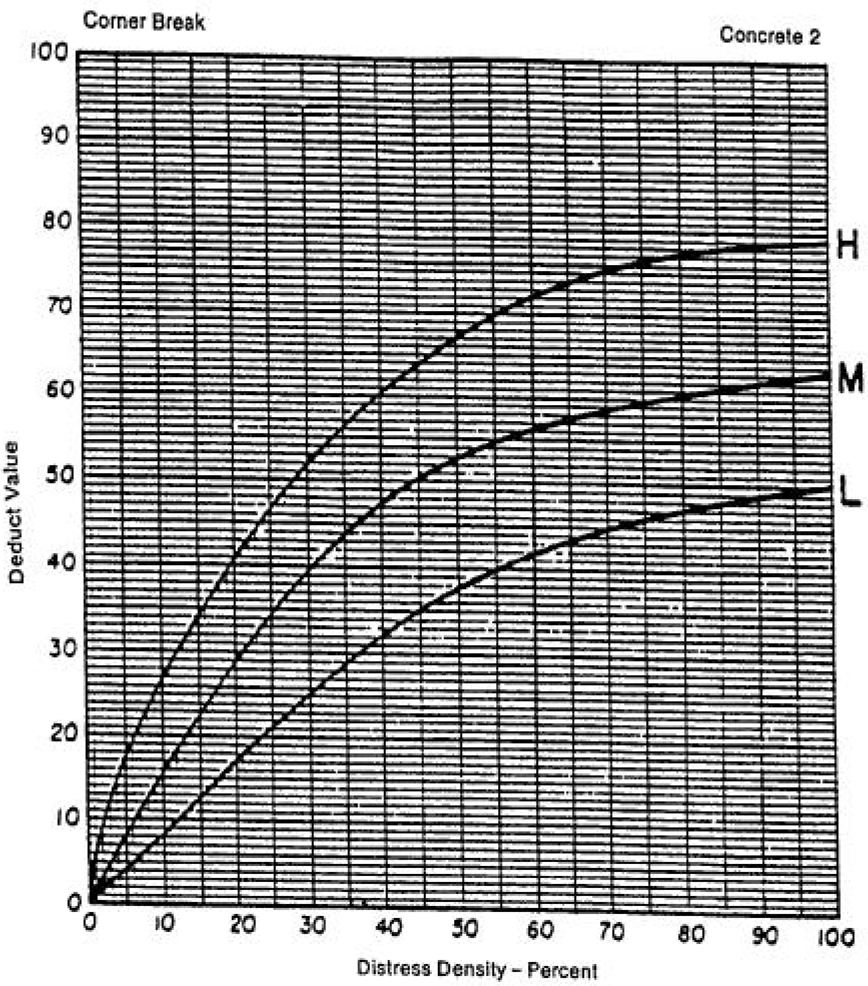
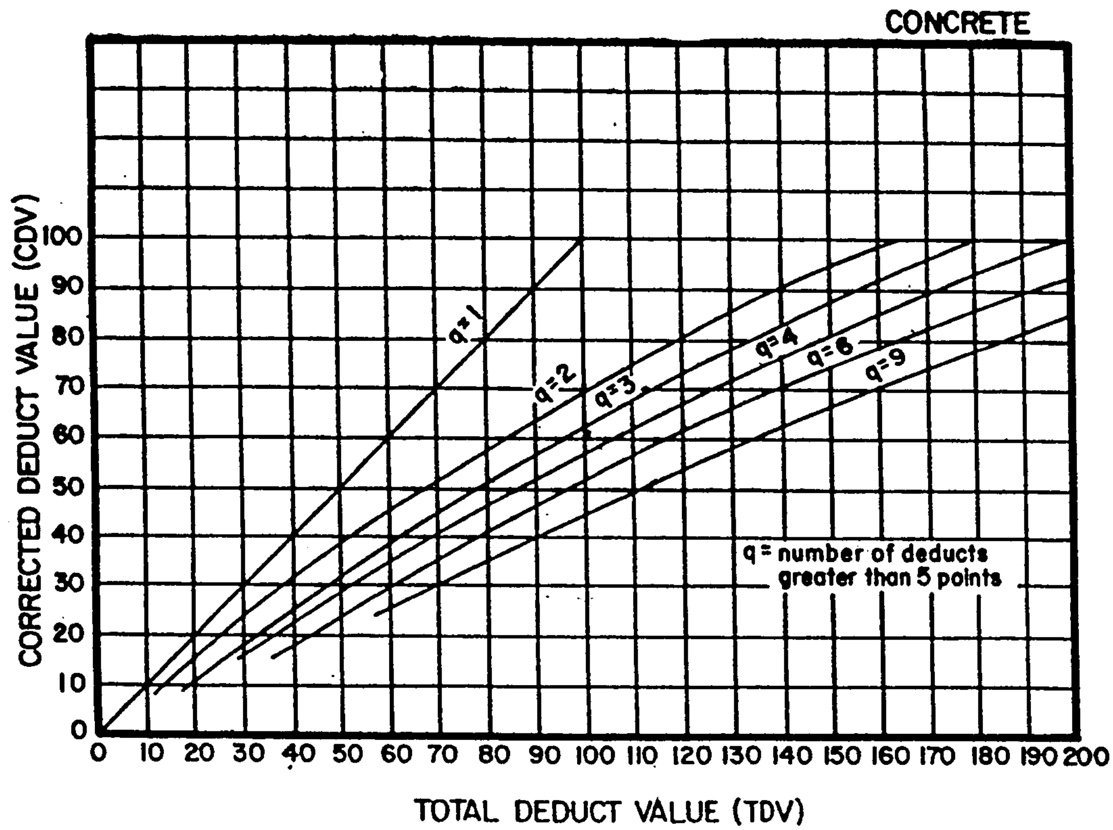


Figure 5.6 Correction Curve for Jointed Concrete Pavement



The PAVER system has proven effective on military installations and in several cities throughout the country. However, its use by local governments has some disadvantages. Among them are:

- Sections must be divided into sample units. Each sample unit requires one data form. This greatly increases the volume of records for manual systems.
- Each distress in each sample unit must be physically measured. This greatly increases inspection time and costs.
- The number of units to be inspected is based upon statistical samplings. If the range of PCI's within a section varies greatly, additional units will have to be inspected, and second or even third field inspections may be necessary.
- The PCI computation may become tedious for a large network.
- For even small networks, manual systems may not be practical.

PAVER has the advantage of being a rather precise distress survey technique which produces consistent results when repeated. The rating procedure produces a meaningful and very accurate measure of pavement condition. PAVER also has the advantage of being supported very actively by the APWA.

Training Raters: For any given method of distress data collection, the accuracy and precision are a function of the training of the data collection personnel, the clarity of distress identification manuals, and the quality control practiced by the agency. The distress identification manuals must be clear so that the rater always has a standard to which to refer. A clear manual and comprehensive training reduce subjectivity. Reference *6* is an example of a distress identification manual used in many agencies across North America.

In most agencies, inspectors only collect distress data a few weeks each year. Annual training sessions are necessary before each distress collection period, even for those who have inspected pavements before. Inspectors are more accurate if they know their work is going to be checked. In general, a quality control program should be established in which a small percentage of the pavements inspected are re-inspected by supervisory staff or other inspection teams. Three to five percent is often used. If the inspections between teams diverge, the inspectors should be put through a refresher training course.

Typical Manual Walking Survey Procedures: In walking surveys, pavement inspection is typically conducted on selected inspection units in the management section. An inspection unit is a small segment of a management section selected of convenient size that is then inspected in detail. SHRP uses inspection units, 120 m long by one lane wide. Typical agencies would use inspection units from 50 to 200 feet (15 to 60 m) long by one to four lanes wide. Generally, inspection units should have a relatively uniform size within a management section. Most states such as Iowa, New Mexico, and Pennsylvania, still use some form of manual surveys. As stated earlier, 40 states still reported using manual or windshield surveys in 1994 (27). However, in recent years, more states are beginning to move towards automated surveys.

The units inspected may be selected at random or through a defined sampling procedure. Some agencies select inspection units to "represent" the section, whereas others select inspection units at a set frequency, e.g. one every quarter kilometer.

The inspector then inspects the sample unit by walking the pavement. The inspection can be completed while standing on the shoulder. The inspector identifies and records each distress type, severity and amount present in the inspection unit. The type, severity and amount must correspond to those defined in the appropriate distress identification manual. The quantities and severities should normally be estimated using measuring techniques as accurate as measuring wheels or tapes to pacing.

Data may be recorded using a hand held microcomputer, a pen based computer (electronic clipboard), or a data collection sheet. The total quantities for each distress type and severity are automatically tallied in the data collection devices. The inspector must sum them after returning to the office if data collection sheets are used.

Typical Windshield Survey Procedure: The windshield survey is conducted from a moving vehicle. Reference *13* is an example of such a survey. The inspector travels the road management section in a vehicle travelling at about 5 to 15 miles (8 to 20 km) per hour. The distresses are visually identified by the rater, and the area affected is estimated as a percentage of the road surface *(13).*

Five distress types, drainage and roughness are rated by the inspector. Alligator cracking, edge cracking, and longitudinal/transverse cracking are each rated with three severity levels and three levels of extent (quantity). Patching/potholes are rated with three levels of extent but without considering severity. Rutting is rated with two levels of severity but without information on quantity. Roughness and drainage are related with three severity levels without information on quantity.

The damage quantities are estimates of the percentage of the entire management section affected and are generally in categories such as *(13):*

Low	the total section length affected is less than 10% of the section length
Moderate	the total section length affected is between 10% and 30% of the section length
High	the total section length affected is more than 30% of the section length

The information is determined as the inspector travels along the road on a single management section and is recorded on a data collection sheet, digitizing tablet, or laptop computer. At the end of the management section, the data must be finalized by completing the data collection sheet or storing the collected data in the lap-top computer.

The collection of distress data using quantity categories limits the use of the data. The change in quantities will not be a smooth function over time. Instead, the change in quantity over time will be a step function, and it often may jump back and forth between categories when the quantity is near a limit of the category, e.g. when the quantity is near 10 or 30% in the example shown above. This can lead to instability in the data over time.

Automated Distress Surveys: Manual distress survey procedures are slow, labor intensive, and subject to transcription errors. Consistency between classification and quantification of the distresses observed by different raters can also be a problem. Once the data has been summarized and corrected for transcription errors, the only recourse for checking apparent anomalies in the data is a return visit to the field. Safety of field crews is also another concern.

To minimize these problems, methods have been devised by various agencies to standardize distress classifications and to speed up the survey process by automating the recording, reduction, processing, and storage of the data. Small hand-held computers and data loggers have been used.

Vehicles, which take photographs or other visual images of the pavement, have been developed to speed the field data collection time and provide a permanent visual record of the actual pavement condition. A new class of condition survey vehicles is emerging which uses objective measures of the pavement surface to classify and quantify different types of distress. The direction of current development in distress survey equipment is the use of video imaging to take a picture of a portion of pavement and, by using pattern recognition technology, classify and quantify distress directly without the subjective evaluation of human raters.

An automated distress survey can be classified as any method in which distress data is entered directly to the computer in the field during the distress survey. This type of automation can greatly reduce errors associated with transcribing data from paper forms as collected in the field into computer files which will be used in road surface management. Other benefits of automated distress surveys include increased safety for survey crews, faster and more accurate surveys, less expensive data collection, and more repeatable surveys.

As mentioned above, imaging and distance measuring techniques are being developed to measure distress *(3,4,14)*. There are several classes of automated data collection and interpretation as summarized below:

1. Distress images are collected on film or high resolution video, image analysis techniques are used to identify type, severity, and quantity of individual distress types while the vehicle collects the data;

2. Distress images are collected on film or high resolution video, image analysis techniques are used to identify type, severity, and quantity of individual distress types in the office after the vehicle collects the data;

3. Distress images are collected on film or high resolution video, a trained observer is used to identify type, severity, and quantity of individual distress types in the office while viewing the images after the vehicle collects the data;

4. Lasers are used to determine changes in surface texture and distance which are interpreted to determine some distress types by computer algorithms;

5. Lasers or other methods are used to measure distance to determine specific distress types such as rutting in asphalt concrete pavements.

In general, as the survey type increases from 1 to 3, the subjectivity increases. The resolution is a function of the equipment used to make the image. In general, 35 mm photography has higher resolution, but it must be digitized for image analysis by computers. Resolution in photography is a function of the film speed, coverage area, and lighting. Video is basically a digitized format when the image is made, and resolution is a function of the number of pixels per distance, the shutter speed, and lighting. The resolution of the laser equipment is a function of the size of the laser point and the analysis algorithm used to convert changes in texture to distress.

Item 5 above recognizes that it is possible to use special equipment to measure certain types of distress. The “rut bar” is the most commonly used. A series of distance measuring devices are placed on a horizontal bar. The differences among the measurements of the devices are used to develop a transverse profile of the pavement surface from which the amount of rutting can be determined. In item 5, the resolution is a function of the number of distance measuring devices and the precision of the distance measuring process. The precision is a function of the number of measuring devices and the location differences between repeat runs.

The precision and accuracy are functions of the interpretations, the lighting, and the placement of the imaging during repeat runs. The laser-based systems have more precision problems because they view small areas which are combined to give estimated distress information. If a repeat run is a few millimeters (inches) off from the location of the first run, the information can be quite different.

For the imaging systems, the images can be affected by shadows from trees, poles, etc. The direction of the sun can also change the image from one time of day to another. Any of the approaches can control the lighting conditions either by enclosing the camera and pavement with fixed lighting or by completing all surveys at night and using fixed lighting. The lights can be set at an angle so that known shadows can be used to help identify crack widths, elevation differences, etc.

One of the selling points for using automated distress survey procedures is that they are less subjective than manual surveys. However, the subjectivity is a function of the type of interpretation. In the simplest form, the images are manually interpreted. The distress identification is still manual; the inspector identifies, quantifies, and records distress from the image rather than from the pavement surface directly. This takes the inspector off the road and reduces traffic interruption, both of which are extremely important for safety on high volume highways, but subjectivity is still present.

The least subjective system is the automated analysis of the images. However, image analysis by automated means has been found to be quite complex. The distresses can take many patterns. This requires pattern recognition algorithms that can distinguish between types of cracks, between a patch and pavement markings, etc. Some distresses such as weathering and raveling do not appear on images very well and must be interpreted based on surface texture or other approaches. The pavement surface texture varies considerably between pavement surface types which must be considered in the interpretation. The fact that colors of pavement surfaces vary considerably must also be considered. All of this has prevented any of the systems from completing a fully automated interpretation process at the time this was prepared.

At the current time, any distress information collected and reduced using automated procedures needs to be carefully analyzed to determine the accuracy, precision, and resolution.

The exception to this is the measurement of rutting with distance measuring equipment, often referred to as “rut bars.” These devices are generally quite accurate, are capable of collecting data more often than could normally be collected manually, and give information in a quantitative form ready to use.

5.6 Automated Condition Survey Equipment

Most states use automated equipment to collect pavement friction, roughness, profile, rut depth, and deflection data. Most still perform visual distress surveys but this process will change drastically in the 1990’s. Table 5.6 contains a list of the primary devices used to collect these indictors. Table 5.7 lists equipment used since the 1940’s, devices used today, and projected equipment beyond the year 2000.

TABLE 5.6 Summary of Primary Condition Data Collection Equipment Used By the States.*

DEVICE	FRICTION	ROUGHNESS	PROFILE	RUT DEPTH	DISTRESS	DEFLECTION
Locked Wheel	Most all					
Mays/Cox		18				
KJ Law 8300/690		9	9			
ARAN		6		5	5	
Laser RST		2	2	2		
SD Road Profiler		24	24	24		
Dynaflect						6
Road Rater						13
FWD						32

*The 50 States, the District of Columbia and Puerto Rico.
Note: Totals exceed 52 in some cases due to concurrent data collection for the purpose of correlating data collected with a new device to the historical database. Totals may also be less than 52 if automated equipment is not used.

Table 5.7 Automated Pavement Condition Data Collection Trends in Technology

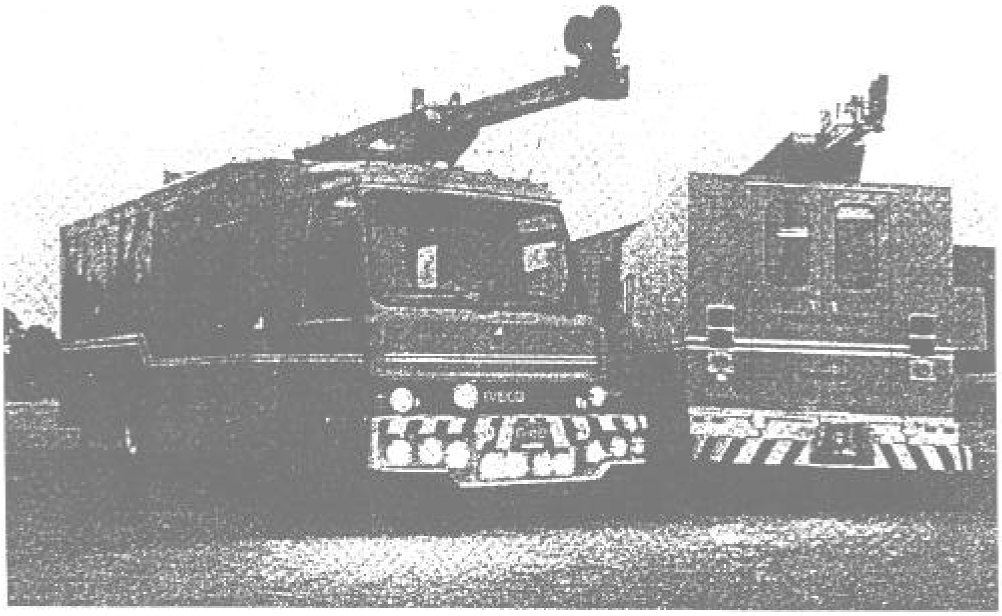
TIME PERIOD	FRICTION	ROUGHNESS	PROFILE	RUT DEPTH	DISTRESS	DEFLECTION
Pre 1940	Subjective ↓	Subjective ↓	NM ↓	Subjective ↓	Subjective ↓	NM ↓
1940 to 1960	LW ↓	RTRRMs ↓	NM ↓	Manual ↓	Subjective ↓	Static ↓
1960 to 1980	LW ↓	Many RTRRMs→ ↓ Profilers ↓	A few ↓ Profilers ↓	Manual ↓	Subjective ↓ & Manual ↓	Steady State ↓ Dynamic ↓
1980 to 1990	LW ↓	RTRRMs & ↓ More Profilers	Increasing No. ↓ of Profilers ↓	Manual, Laser ↓ Acoustic ↓	Subjective, Acoustic ↓ Laser & Video ↓	Steady St. Dyn. → ↓ Impulse ↓
1990 to 2000	LW→Video ↓ &/or Laser? ↓	Mostly Profilers ↓	Profilers ↓	Acoustic & ↓ Laser ↓	Video & Image ↓ Processing ↓	Impulse ↓
Beyond 2000	Laser or Video?	Profilers	Profilers	Laser or Video?	Image Processing & Pattern Recognition	Laser or Video?

LW = Locked Wheel Skid Trailer RTRRMs = Response Type Road Roughness Meters NM = Not Measured
Predicted use based on information received from state PM practitioners, researchers, and equipment suppliers (shaded).

Distress: Most State Highway agencies still use a visual survey as the basis for distress data collection. The manual process, however, will be transformed to a highway-speeds data collection process during the 1990's. The subjective visual distress survey has been enhanced considerably by the addition of condition survey keyboards. The keyboards permit the rapid entry of large quantities of data, and eliminate transcription errors since data is uploaded electronically to the central database.

Several technologies hold great promise for accomplishing high-speed distress data collection: laser technology, film-based systems, and video systems. Laser systems detect some cracking, but reliability and repeatability is poor. In addition, no visual record of the condition is available. Film-based systems such as the PASCO Road Survey System (Figure 5.7) being used by the Strategic Highway Research Program provide very highly resolved, proportionally scaled images of the pavement surface. Other agencies using the PASCO system are the Arizona, Connecticut, Illinois, and Iowa Departments of Transportation.

Figure 5. 7   PASCO Road Survey System

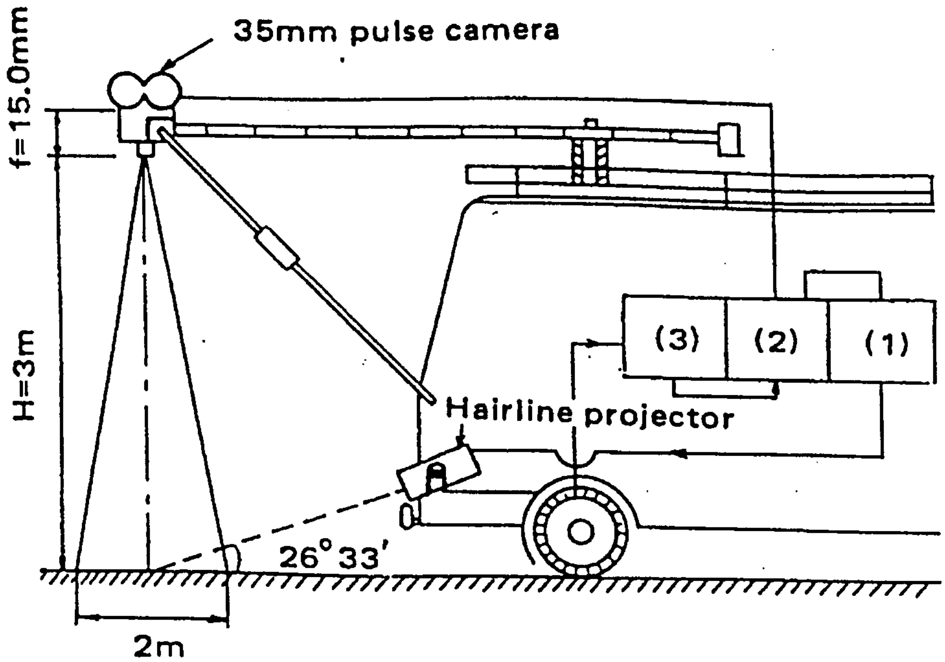


The PASCO 35-mm film technology produces a continuous film of the pavement that can be readily digitized with automated equipment. The system operates at night using external illumination to emphasize distresses on the film. Widths of up to 16 ft. can be photographed with the system. In the office the strip film is processed, and distresses are manually measured on a film digitizer. Any type of distress on any type of pavement can be determined. A similar system, the GERPHO has been used in France since the mid-1970's.

PASCO has developed a system to measure rut depth and transverse profile across a full lane width. A rear-mounted camera photographs a hairline projected on the pavement surface by a pulsing strobe light. (Figure 5.8). Measurement intervals can be programmed by the operator. Fifty-foot intervals are usually selected. The photographed hairline parallels the pavement surface. Using the fixed geometric configuration of the camera and strobe projector the rut depth can be accurately measured in the office. Excellent correlation between manual measurements and the PASCO process have been recorded.

Figure 5.8 PASCO Road Survey System Rut Depth Measurement

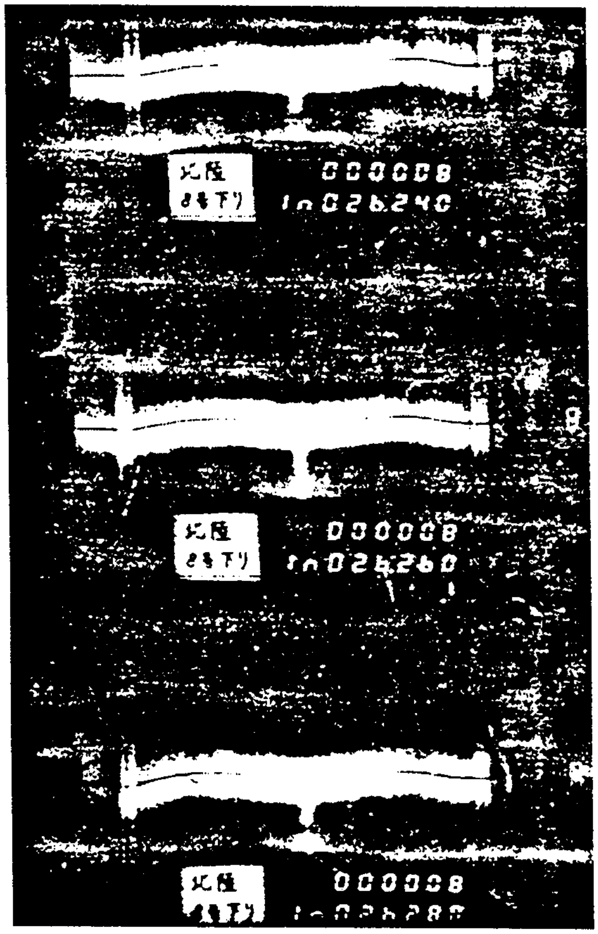
Rut Depth Field Data Collection



(1) Hairline projector control unit
(2) Camera control unit
(3) Pulse signal transmission device

Figure 5.8 PASCO Road Survey System Rut Depth Measurement, cont.

Filmed Rut Depth - Hairline Images



The cost of the PASCO system exceeds most state’s budget for network level surveys. Video systems hold great promise as a low-cost, reusable substitute for film, and eliminates film development.

The ARAN, the Australian Road Evaluation Vehicle, the MHM Associates ARIA system, Pavedex’s PAS-1 device, the PaveTech VIV unit, and the VideoComp trailer use videos to record pavement images. The Roadman-PCES system uses a line camera and slightly different process. Depending on the device 1,2,3,4, or 5 cameras record surface distresses. Multiple camera installation permits detection of 1/8” or finer pavement surface cracks. Table 5.8 compares the relative cost and resolution of various image media.

Table 5-8 IMAGE MEDIA COMPARISON

MEDIA	RELATIVE COST	LINES OF RESOLUTION
35 mm Film	High	1700 – 3500+
VHS	Low	250+
¾- inch Video Tape	Low	340+
S-VHS	Low	400+

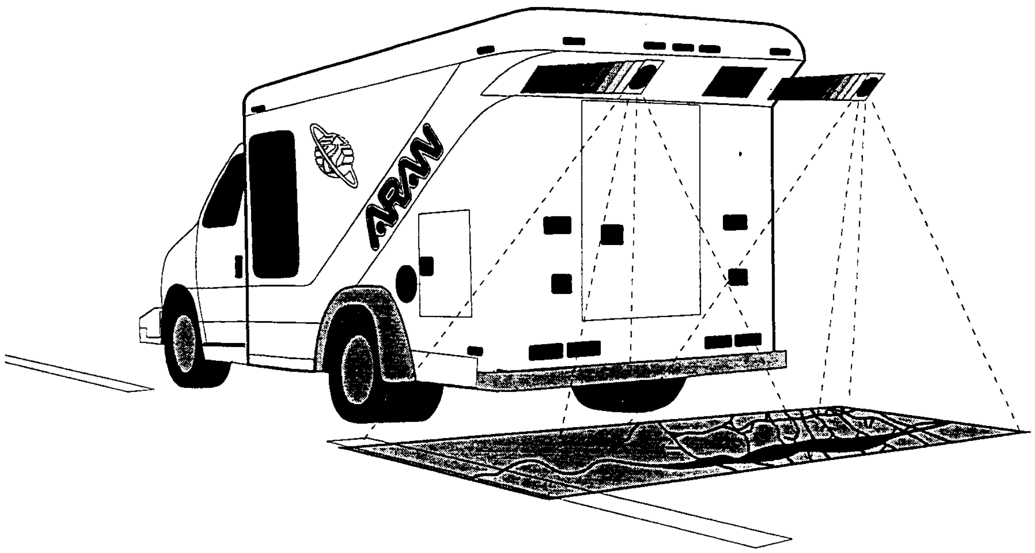
The *ARAN* is a high speed, multi-functional, and diverse road/infrastructure data acquisition vehicle. It has the capability to measure pavement condition and distresses required for comprehensive pavement management. User agencies of the *ARAN* include state, county, and city transportation departments in over 20 countries worldwide, 30 states within the United States, and 7 of the 10 Canadian provinces.

Two different onboard geometric subsystems are employed. The Standard Onboard Geometrics and Orientation System employs three aircraft gyroscopes and accelerometers that continually measure the roll, pitch, and heading of the *ARAN*. The POS/LV Onboard Geometrics and Orientation System utilizes state-of-the-art military aircraft grade gyroscopes, accelerometers, and Global Positioning System (GPS) receivers all working in concert to provide enhanced survey level precision measurements. The *ARAN* employs GPS to continuously monitor the *ARAN*'s absolute position in XYZ space with an accuracy of 50 to 100 meters.

ARAN employs two road roughness profile measuring systems. The Laser SDP employs the use of lasers instead of ultrasonic sensors. The second road roughness profile measuring system is an inertial roughness profilometer. The *ARAN* also used a "Smart Bar" for road rutting measurements. The "Smart Bar" employs up to 37 ultra-sonic sensors positioned at four-inch intervals across the entire transverse profile of a 12-foot lane. The rut is then measured to an accuracy of 1/32 of an inch. Most states owning an *ARAN* measure rut depth using 13 sensors, obtaining a transverse point every 12 inches.

Video logging is used to collect data. The *ARAN* can employ up to six video cameras. The two onboard video logging subsystems are the Right-of-Way (ROW) windshield video and the Pavement View (PV) video. The ROW consists of a full color video camera mounted between the driver and passenger and looks forward out of the vehicle's front window to record a continuous video as seen through the windshield.

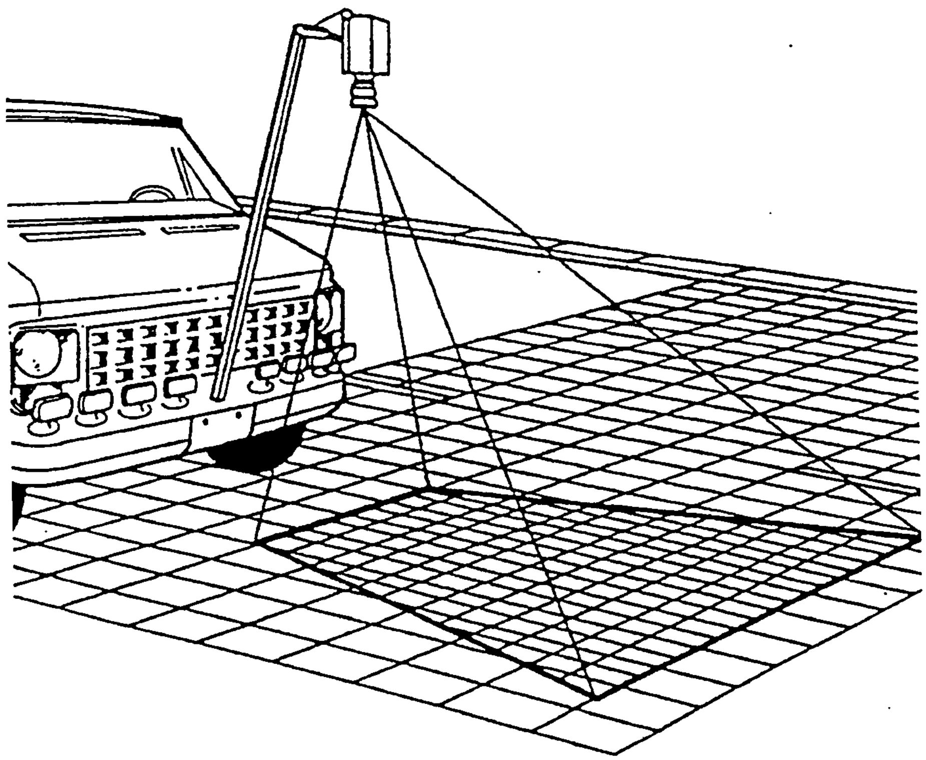
Figure 5-9 The Automatic Road Analyzer (ARAN)



MHM Associates are the suppliers of the Automated Road Image Analyzer, *ARIA* (Figure 5.10). The *ARIA* has the capabilities of measuring both pavement distress and rut depth. The user vehicle for the *ARIA* is generally a van, which can operate at speeds of 10 – 50 mph. The system components consist of a video camera to collect data, a distance measuring instrument (DMI) for data referencing to an accuracy of 1/100 of a mile, and automated digitized processing through video imaging to analyze acquired data. The minimum size crack that *ARIA* can detect is 1/8 – 1/16”.

Currently, the *ARIA* is used primarily at the local level, such as the City of Corisicana, Texas, and LaPorte County, Indiana.

Figure 5.10 MHM Associates, ARIA



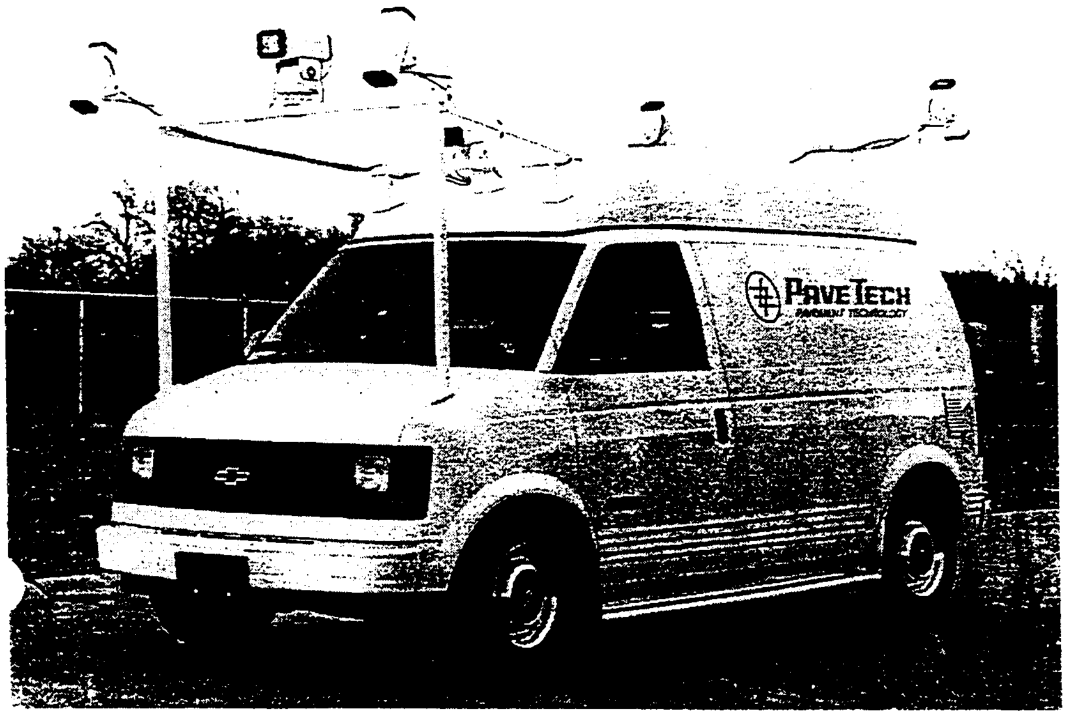
Pavedex Inc. is the supplier of the *PAS-1*, another automated pavement distress collector (Figure 5.11). The user vehicle for the *PAS-1* is a van that has the capacity to operate at speeds from 0 to 55 mph. The system components consist of five video cameras, 2 on the front, 2 on the rear, and one top center mount. Each camera can cover a span of 30 square feet, with a 50% overlap at 55 mph. The cameras record pavement distress and the system utilizes automated digitized processing through video imaging to determine cracks with a width as small as 1/16". The DMI used in the *PAS-1* can measure with an accuracy of one foot. The *PAS-1* also employs a road videolog, which is suitable for inventory of signs, as well as roadside and condition monitoring.

The Pavedex *PAS-1* is currently being used in 10 counties and 4 cities in the western United States. Evaluations have been completed by Caltrans, Washington DOT, Iowa DOT, and the Kansas DOT.

Figure 5.11 Pavedex PAS-1

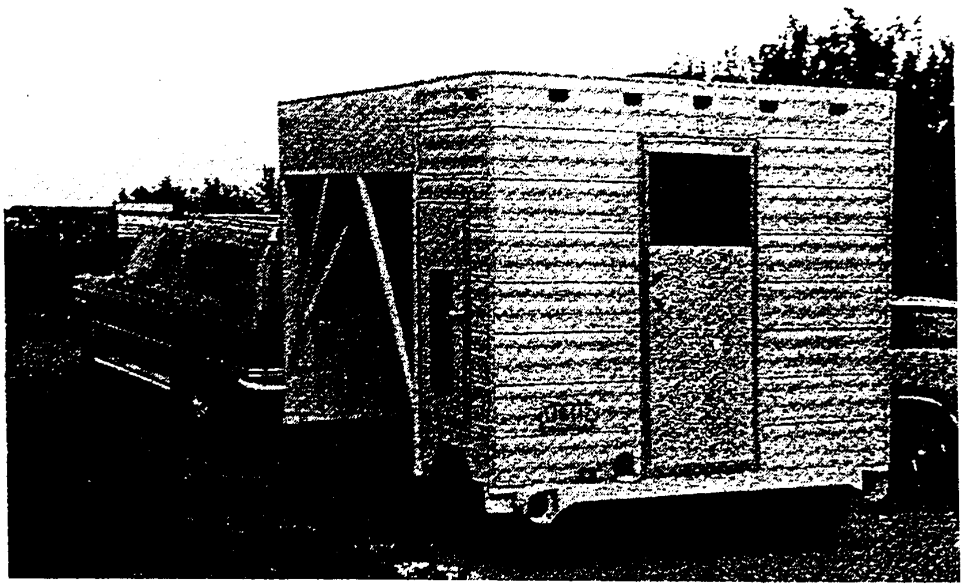
PaveTech Inc. is the manufacturer of the *PaveTech Video Inspection Vehicle (VIV)* shown in Figure 5.12. The *PaveTech VIV* is an automated pavement distress collector that utilizes five video cameras, similar to Pavedex's PAS-1, to measure pavement distress, roughness, rut depth, and road profile. The user vehicle is a van, which operates as speeds from 0 to 60 mph. The system components consist of the cameras, accelerometer(s), ultrasonic sensors, and a DMI with an accuracy of less than 0.5%. *PaveTech VIV* uses this equipment to measure cracks with a width greater than or equal to 1/16", produce the roughness in IRI, the PSI, the rut depth profile, distress in three dimensions, and a raw distress database.

Figure 5.12 PaveTech VIV



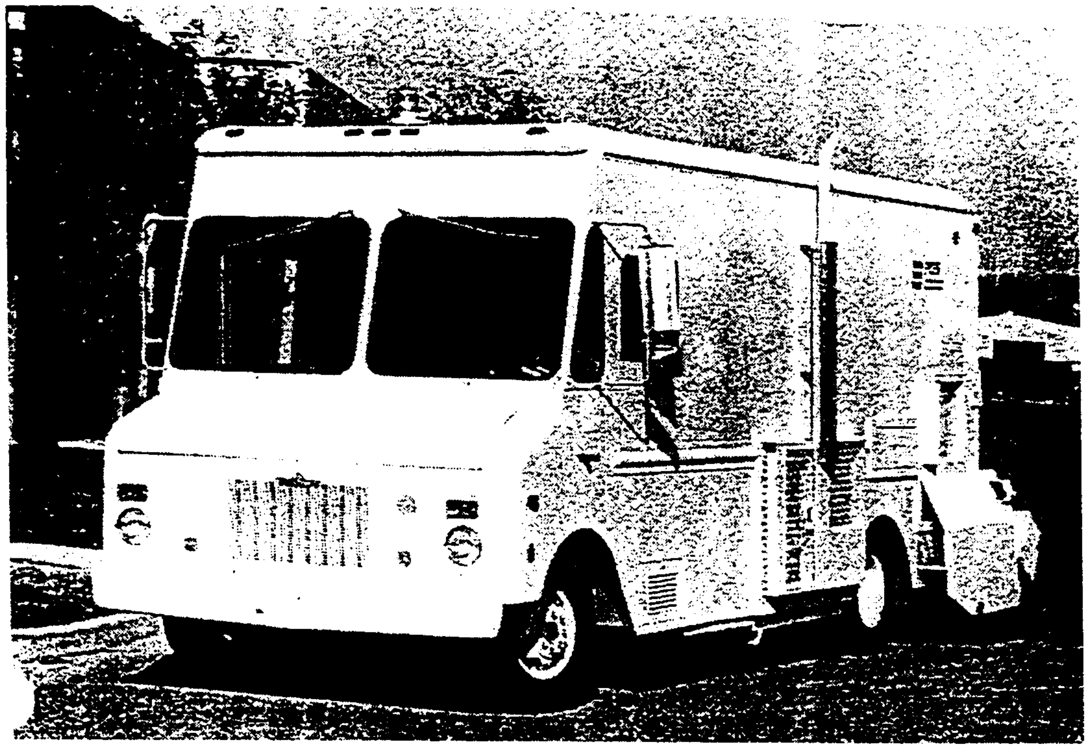
VideoComp (Figure 5.13) is a automated data acquisition vehicle that measures pavement distress. It is contained in a trailer that is towed behind a suitable vehicle at speeds of up to 60 mph. The data is collected through the use of 4 video cameras, which have the capability to measure cracks with a minimum width of about 1/10”. *VideoComp* uses four 500-watt lamps adjacent to the cameras that are mounted in the trailer to provide additional lighting. It also utilizes a monitor that checks all cameras during data collection. The output from *VideoComp* is a crack map that illustrates the location and extent of cracking on the road.

Figure 5.13 VideoComp Trailer



Roadman-PCES Inc. is the manufacturer of the *Pavement Distress Imager (PDI-1),* illustrated in Figure 5.14. The *PDI-1* uses a step van on a 21-foot Grussan truck body, operating at speeds of 0 to 60 mph, to record pavement distress through a continuous line scan videolog. The *PDI-1* measures pavement roughness through the use of a ultrasonic transducer and a linear accelerometer. It has the capacity to measure crack widths as small as 1/20”.

Figure 5.14 Roadman-PCES



The following equipment measure rut depth and/or surface roughness.

The *ITX Stanley Road Tester 3000* is a pavement survey device housed in a standard van, or similar vehicle, that surveys distance, longitudinal profile, roughness, pavement surface distress, and rut depths. It incorporates image capturing and global positioning and is typically operated at speeds of up to 50 mph.

A transmission driven DMI is used to measure distance along the traveled pavement section. The DMI transducer produces electronic pulses at a set frequency and operating software translates the signals into a traveled distance and records it as a reference point for data being simultaneously measured/collected by each of the other operating subsystems.

The *RT 3000* measures longitudinal profile and roughness through the use of 3 transducers; a height sensor which measures the distance between the vehicle and the pavement surface while the vehicle is traveling at up to posted speed; an accelerometer which measures the vertical accelerations of the vehicle as it bounces in response to the pavement surface profile; the DMI to provide a reference measurement of the vehicle as it traverses the road. Operating software and post processing software combine the three measurements, eliminating the effects of vertical vehicle motion and thereby defining the vertical profile of the pavement surface. The longitudinal roughness profile of each wheel track is obtained using an accelerometer and height sensor in each wheel track.

The *RT 3000* also employs a surface distress recording subsystem. It includes specially designed data entry keyboards to automate the entry into the central computer of observed surface distresses. The system identifies a wide range of distress manifestations, identifies the severity in three classifications (low, moderate, and severe) and quantifies them in a number of area coverage categories.

Rut measurements are conducted using a 5-sensor rut bar mounted in the front bumper position on the survey vehicle. One sensor is placed in the center of the vehicle, one sensor mounted in each wheel path, and one sensor placed outside each wheel path. This configuration enables the calculation of each wheel track rut separately.

There is also a video-based system consisting of two or three cameras and two super VHS video recorders. The cameras can be mounted facing downward, capturing an image of the pavement surface, and facing forward, capturing the street-scope from which the right-of-way data can be extracted. The *RT 3000* uses a Global Positioning System (GPS) to collect the position coordinates of any roadway feature of interest and record its detailed attributes.

The *Laser RST* is a multi-function testing vehicle that was developed in Sweden and is used by Infrastructure Management Services (IMS) in North America. The *Laser RST* uses laser technology to identify the distress, profile, roughness, rut depth and macrotexture of a pavement. The system consists of video cameras, accelerometers, laser sensors, a distance measuring instrument and a computer system. The system uses 11 laser sensors to collect data. Four of the sensors are used for identification of cracks and the remaining sensors are used to collect information on rutting and microtexturing. The data can be collected for small sections, such as block by block, or for long stretches of roadway. The information is collected and is stored in a data file. The data file is then imported into a software program that is developed for each agency based on the protocol specified. The system also has the capability to calculate an IRI for the pavement in real time. The vehicle has the option of being equipped with a GPS system.

The *GIE System* (GIE Technologies) performs a detailed assessment of the current state of the road network and its weaknesses, provided by state-of-the-art instrumentation loaded on board a specialized vehicle traveling at the speed of regular traffic. The specially fitted vehicle is equipped with a laser system, called BIRIS, which captures data on the roadway surface conditions, such as ruts and cracks, and the longitudinal and transverse profiles of the road surface. In addition, the vehicle may be equipped with a stereoscopic imaging system for roadway features, a georadar system to capture data on the condition of sub-surface structure layers and an infrared camera to detect problems with the adherence and lamination of multiple surface materials and bridge sections. The vehicle is also equipped with a GPS system for automatic positioning of roadway data.

The BIRIS laser beam technology is a telemetric and photometric sensor using laser beams to collect information. Using the dual irises in the sensor's optical system, the technology generates calculations of the distance to an object intersected by the laser light beams. Using a set of six sensors, the vehicle is equipped to inspect surfaces measuring up to 3.6 meters (12 feet) in width.

The *GIE System* generates continuous measurement of various parameters including: roughness of the surface using IRI international standard; type severity and extent of defects in three dimensions, using SHRP and MTQ (Ministere des Transports du Quebec) standards; continuous longitudinal profiles in both wheel paths; transverse profiles acquired at regular intervals across the path of travel; positioning and measurement of ruts; cracks and other defects; reconstitution of defects in three dimensions; classification of quantitative information; digitized photometric image of the roads surface; and characterization of the road surface geometry (gradient and crossfall).

A comprehensive analysis of the data is provided by a highly specialized management program called PEAK. The information collected by the laser, georadar and infrared camera on the defects on the road surface and structure are processed and classified by a computer on board the vehicle. Subsequently, compressed and archived data are analyzed by the PEAK software, which extracts relevant information. PEAK conducts a preliminary diagnosis and identifies the causes and processes of road deterioration.

Another automated pavement distress collection system is the *Road Surface Analyzer (ROSAN)*. The *ROSAN* series made its debut in 1997 after being developed at the FHWA's Pavement Surface Analysis (PSA) Laboratory at the Turner-Fairbank Highway Research Center (TFHRC).

The *ROSAN* devices electronically record macrotexture characteristics of pavement surfaces, some at highway speeds. It incorporates a laser sensor, accelerometer, and distance pulser in a unit mounted on wheels. The *ROSAN* comes in four models, each with different operating characteristics:

The $ROSAN_{bp}$ is the first in the series and has two modes of operation. In the (b) mode, a computer-controlled trolley carries the laser sensor across a stationary 1-m reference bean. In the (p) mode, the entire unit is manually pushed or pulled. Outputs include macrotexture, grooving, and faulting.

The $ROSAN_v$ incorporates a laser sensor is mounted on a vehicle bumper and can be operated up to speeds of 60 mph. Data can be recorded continuously for distances of 800 to 2300 feet, depending on data collection mode. The unit can be mounted on almost any vehicle fitted with a simple bumper-mounted trailer hitch. Outputs include macrotexture, faulting, and grooving.

The *ROSAN*$_{vm}$ uses a computer-controlled motorized trolley that guides a laser sensor along a beam that is mounted on the front of a suitable vehicle. The beam can be one of three lengths and operated up to speeds of 60 mph. Outputs include left wheel path, center, and right wheel path macrotexture and faulting, grooving, rutting and slope.

The *ROSAN*$_{vm(P)}$ is the last in the *ROSAN* series and takes the *ROSAN*$_{vm}$ one step farther. The (P) refers to profiling, where the IRI is analyzed using FHWA's PRORUT II software.

The *ROSAN* series are available for loan to State Highway Agencies, researchers, pavement management personnel, and other interested in measuring and evaluating the macrotexture depth of pavement surfaces.

KJ Law is another manufacturer of automated pavement distress collection equipment. One model manufactured by KJ Law is the *KJ Law T6400*, a lightweight profilometer designed primarily for new or overlay pavement smoothness control. The system can be used to profile new road surfaces within hours after paving, allowing necessary potential corrective action to be taken before the surface is fully hardened.

The basic system consists of a precision accelerometer, an infrared non-contact height sensor with a large footprint, a graphic display, an IBM-compatible computer, and a parallel graphics printer. Inputs from the accelerometer and sensor are fed to the system's onboard computer, which calculates and stores true profile and a roughness index. The system operates at speeds between 5 to 15 mph.

Another model is the *KJ Law T6500*, a profilometer system, which measures and records pavement profile in each wheel path and rut depth. The basic system features two precision accelerometers and three infrared sensors.

The system's onboard computer can calculate one real-time, profile-based road roughness index and one off-line index. The program for rut depth computes and stores average rut depth every 100 feet from data taken every three feet, or at other selected intervals.

The system components are: three or more infrared sensors; an accelerometer for each wheel path; a VGA display; a computer with an industrial hardened 486 processor; and, a parallel graphics printer. Selected options will provide transverse profiles with rut depth measurements, geometrics, right-of-way videologging, pavement surface videologging, and a geographic positioning system.

A final model is the *KJ Law T6600*, a non-contact profilometer with an inertial system that measures and records pavement profile in each wheel path. The basic system consists of two precision accelerometers and three infrared sensors, which, when the inputs are fed into the system's onboard computer, produces pavement profiles, rut depths, and roughness indexes.

The system's onboard computer can calculate one real-time, profile-based road roughness index and one optional index. The program for rut depth computes and stores average rut depth every 100 feet from data taken every three feet, or at other selected intervals.

The system components are three or more infrared sensors, an accelerometer for each wheel path, a VGA display, a computer with an industrial hardened Pentium processor, and a parallel graphics printer. Selected options will provide transverse profiles with rut depth measurements, geometrics, right-of-way videologging, pavement surface videologging, and a geographic positioning system.

The *DYNATEST 5051 RSP* test system is a road surface profiler. It consists of a mechanical/electrical transducer beam mounted on a minivan or full size van. The test system is able to measure, display, store, and calculate longitudinal road profile and roughness data in both wheel paths, including rut data, plus vehicle position and speed. The system is able to operate at speeds up to 50 mph.

The transducer beam consists of three laser displacement sensors and two accelerometers. To measure rutting, five lasers are required. A maximum of eleven lasers can be mounted on the beam to allow for the measurement of transverse profile. Each laser has the capacity to measure vertical displacement to a resolution of 0.001 inches or better.

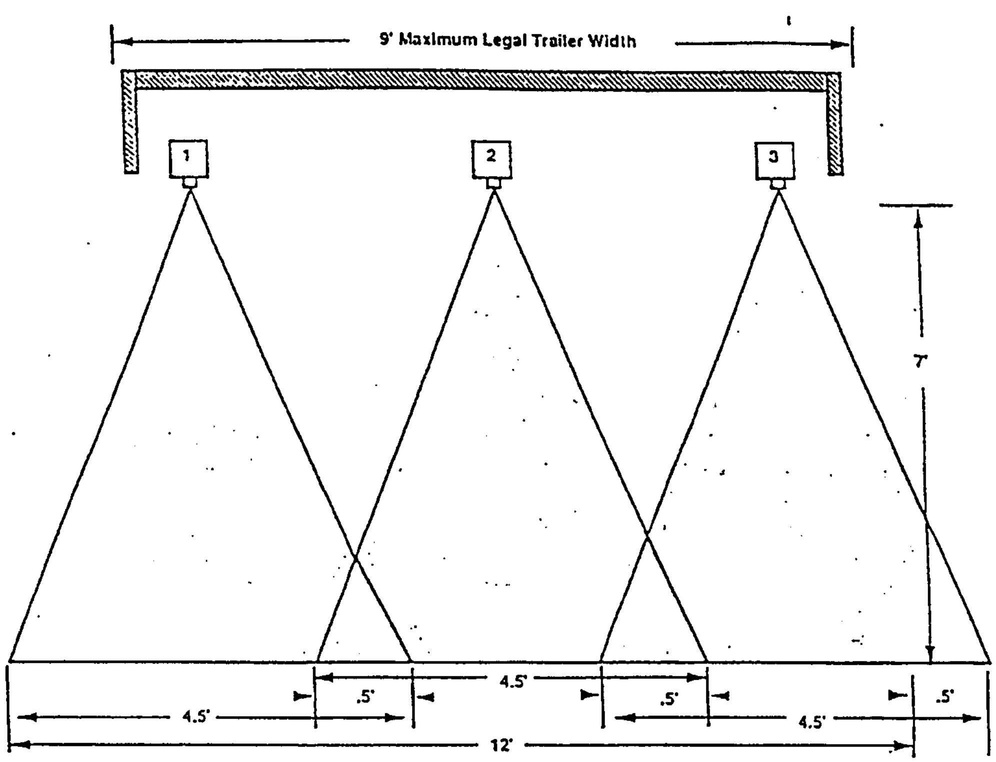
An electronic, microprocessor-based signal conditioning and processing system allows for the interpretation of the laser sensors, accelerometers, and distance/speed encoder. It is based on the same principle as the South Dakota profilometer and computes the longitudinal profiles of both wheel paths in real time.

Procedures and process to fully automate the reduction of data from video-captured images is underway in both the public and private sectors. Several university research centers are examining the process in detail. NCHRP Project 1-27 "Video Image Processing for Evaluating Pavement Surface Distress" is nearing completion. The project objective is to develop, evaluate, and deliver a set of algorithms for processing video images to identify, quantify, and classify pavement distress at highway speeds, noting 1/16" cracks and other pavement distress types and patterns.

MHM Associates, IMS, Pavedex, PaveTech, Roadman-PCES, Inc., and VideoComp are developing processes to fully automate distress data quantification from video-obtained images. Both the hardware data collection equipment and the data reduction and analysis software processes vary considerably. Each vendor/manufacturer is developing a system to meet specific needs of their potential primary users. PCES-Roadman uses a high-intensity illumination system. VideoComp uses a partially contained illumination system. The others operate in daylight, and require more sophisticated software analysis to remove shadows of passing vehicles, clouds, overhead structures, and vegetation and the effects of the changing angles of the sun throughout the day and during the year.

Complexity ranges from reasonably simple (other than software analysis, which is extremely complex regardless of the system) to extremely complex. The VideoComp design was based on the Idaho DOT stipulation that “off-the-shelf” components be used for the system, including the video cameras, recorders, distance measuring instrument and the illumination. PCES-Roadman, on the other hand employs sophisticated technology with line cameras to provide “real-time” processing of pavement images. VideoComp uses 3 cameras plus a fourth camera with a wide-angled lens to record a full-width pavement section (Figure 5.15).

Figure 5.15 VideoComp Camera Arrangement and Pavement Coverage



Roadman-PCES uses 2-4 cameras depending on the specified resolution. Two different mounting heights allow analysis of varying partial-width pavement sections. Pavedex and PaveTech use 5 cameras; 2 each on the front and rear of the vehicle aimed downward at the pavement surface, and a front, horizontally-mounted camera to provide a right-of-way perspective.

It is very important to note that enhancements to all of these systems continue unabated. Communication with state highway agency users and the vendor/manufacturers is highly encouraged before using any distress data collection device. FHWA encourages all state highway agencies to automate the distress data collection process; using an automated system of their own choice based on the pavement distress prevalent on their system, and their budget. Most vendors will provide reasonably priced demonstrations if requested depending on geographic proximity to the state. Table 5.9 summarizes past, present, and projected future use of pavement distress, data collection equipment.

Table 5.9 Distress Equipment Trends

DEVICE OR PROCESS	NO. MID '80s	NO. 1990	NO. MID '90s
Visual Survey	23	37	15-25
Techwest or Photolog	7	1	0
ARAN or other video	0	5	15-25
Visual + Still Photo	3	3	2-5
Film	0	0	0-5?
Video + Image Processing	0	0	0-40?

Distress Equipment References: In June 1990, the Iowa DOT, FHWA and the Iowa State University sponsored the *Automated Pavement Distress Data Collection Equipment Seminar* in Ames, Iowa. Iowa State hosted the conference and produced an excellent proceedings documenting the presentations at the conference, listing equipment exhibitors and demonstrators, field survey results, and a list of some of the most commonly asked questions about pavement distress and pavement condition data collection equipment.

The technology in the area of pavement distress data collection and analysis is changing at a phenomenal rate. Image processing and pattern recognition systems will soon reliably, if not cost-effectively locate and quantify pavement distress from film or most likely, video images.

Equipment Evaluations: A number of States have completed good evaluations of automated equipment during the past several years. Recent evaluations were performed by Washington, Pennsylvania, Iowa, and North Carolina. All had similar approaches to their evaluation i.e. they selected sections, invited (or paid) automated equipment vendors to perform the surveys, and then compared the results with manual surveys. In early 1997, both Pennsylvania and Washington completed studies to evaluate the equipment. Initially, the types of distresses that would be used to make decisions were defined. In the process, Pennsylvania developed an automated distress manual that closely followed the SHRP manual *(9)*.

Control sites were selected for the surveys, and the results of all the vendors were compared with manual surveys. The manual surveys were performed in great detail by experienced inspectors.

The results were mixed; in some cases, the variability in the automated equipment was greater than that for the manual distresses, while for others, they were similar. No over-riding trends were found from all the states. In fact, the conclusions reached sometimes contradicted another state’s.

However, it was clear from the studies that agencies need to carefully examine the distress data needs, and to prioritize them accordingly. Some equipment do not perform well with hairline cracks, or if moisture is present. Others only cover pavement that is the width of the vehicle, and so may miss distresses along the edge of the pavement or between lanes. None can measure raveling. The importance of setting up an appropriate location referencing system prior to the surveys is also critical, as Louisiana discovered.

Table 5.10 summarizes the various automated evaluation equipment discussed.

Table 5.10 Automated Crack/Distress Evaluation Equipment

Equipment	Data Output	Minimum. Crack Width Identified	Line Camera	Laser	Film-Based	Photometrics	Video System
Pasco Road Survey System	Continuous film: digitized in office	1/16”			√		
Pathway Services, Inc.	Video record						√
ARAN	Video record	1/16”					√
AREV		1/16”					√
ARIA System (MHM Assoc.)	Video imaging[1]	1/8”					√
PAS-1 (Pavedex, Inc.)	Video imaging[1]	1/16”					√
VIV (PaveTech, Inc.)		1/16”					√
VideoComp	Crack map	1/10”					√
Roadman PDI-1 (PCES, Inc.)	Continuous line video log	1/20”	√				
ITX Stanley Road Tester 3000	Video record	1/16”					√
Laser RST (IMS)	Crack characteristics – ASCII file	1/16”		√			
GIE System	Crack characteristics/ photometrics	1/8”		√		√	

[1]Video Imaging – Video Record to be digitized in office

There are several advantages to these vehicles. Generally, they have capabilities to collect additional information such as signs, and to obtain a photolog of the highway.

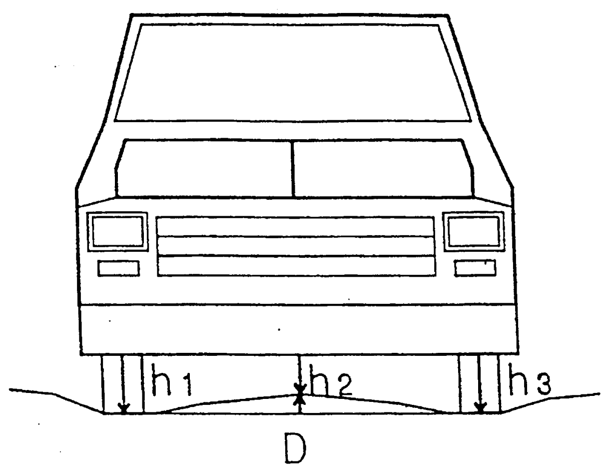
Most are equipped with computers to collect the data, although none can offer real-time processing as yet.

RUT DEPTH: Rut depth measurement at highway speeds is now as routine as profile measurement and roughness data collection. Several devices have been developed to measure rut depth such as the South Dakota Road Profiler, the Automatic Road Analyzer (ARAN), the Laser Road Surface Tester (RST), Pathway, IMS, PaveTech, and the PASCO Road Survey System. The first six use the inertial reference principal previously described. PASCO uses its own patented process.

The Road Profiler estimates rut depth using the ultrasonic transducer in the left wheelpath (which also is used in the profile measurements). Two other transducers mounted in the center of the vehicle and the right wheel path provide three data points for rut depth estimation. Rut depth is computed as shown in Figure 5.16 where h_1, h_2, and h_3 are the respective distances between the roadway surface and the left, center and right sensors. This actually represents the height of the hump between the wheelpaths. The three sensor system was selected to eliminate overwidth extensions which are required to collect a full transverse profile. Rut depth data is collected every two feet, and averaged and recorded every ten feet. A few states have purchased 5-sensor units to better estimate rut depth.

In recent years, more and more equipment vendors have developed techniques to measure rut depth that meet the proposed AASHTO protocols. The field is constantly and rapidly changing, with new equipment and technology being developed. It is beyond the scope of this workbook to provide a comprehensive survey of all equipment. Agencies are advised to contact the FHWA for updated lists of vendors.

Figure 5.16: Rut Depth Estimation with the South Dakota Road Profiler



$$D=(h_1-2h_2+h_3)/2$$

The Laser RST uses eleven 32 kHz lasers in place of the ultrasonic sensors to measure the transverse profile using the inertial reference principle. The projected laser beam is reflected at an angle and received by a photodiode array. Elevation differences are computed using the principle of triangulation. Rut depth is measured continuously and averaged every 15 ft. The accuracy of the device is about 0.002” to 0.02” depending on the pavement texture.

Table 5.11 provides a comparative summary of equipment operating characteristics, accuracy, and number of agencies using each device. The ultrasonic sensors used on the South Dakota Road Profiler, KJ Law 8300A, and ARAN considerably reduce the device initial fabrication and operating costs compared to the optical profilometer or the laser devices. Acoustic sensors are not as accurate as the optical sensors, and short out when exposed to water. Their cost however, is much less than 1% of the optical sensors. Accuracy is suitable for network level surveys, and most project level survey needs. Table 5.12 summarizes the automated rut measurement equipment discussed.

Table 5.11 Acoustic and Optical Technologies

CRITERIA	ACOUSTIC SYSTEMS	OPTICAL & LASER SYSTEMS
No. of State Users	**33**	**7**
Measurement Principle	**Speed of Sound through Air**	**Triangulation**
Accuracy	**0.04” – 0.08”**	**0.002” – 0.02”**
Factors that affect Accuracy	**Temperature, wind, texture, moisture**	**Wind, texture, & ambient light**
Repeatability	**Good**	**Good**
Reliability	**Good if kept dry**	**Good**
Cost of 1 Replacement Sensor	**$20**	**$10,000 - $15,000**
Operating Cost - $ per lane mile	**$2-$6 (owner agency) $15-$25 (vendor)**	**$ varies by vendor and agency**
Cost of Data Collection System	**< $50,000**	**> $250,000**

Table 5.12 Automated Rut Measurement Equipment

LASER (Infrared Sensor) Vendor	Device	Operating Speed (km/hr)	Width Measured (mm)	Sensor Spacing (mm)	Transducer Frequency (Hz)
Dynatest	RSP 5051	Up to 100	3353	838	0 to 300
Pasco	RST	8 to 87	3200	N/A	N/A
KJ Law	T6600	16 to 112	N/A	N/A	N/A
KJ Law	T6500	32 to 112	N/A	N/A	N/A
Infrastructure Management Services (IMS)	Laser RST	8 to 89	3200	291	N/A
GIE Technologies	BIRIS	Up to 80	3658	900	60
ACOUSTIC (Ultrasonic Sensor) Vendor	**Device**	**Operating Speed (km/hr)**	**Width Measured (mm)**	**Sensor Spacing (mm)**	**Transducer Frequency (Hz)**
ITX Stanley	RT3000	0 to 100	N/A	N/A	N/A
South Dakota DOT	Road Profiler	8 to 97	N/A	N/A	N/A
PaveTech, Inc.	PaveTech	0 to 97	3658	N/A	125
Roadman-PCES, Inc.	PDI-1	0 to 97	1219	N/A	125
Highway Product International	ARAN	32 to 105	3658	102 - 305	N/A
Pasco	Roadrecon	0 to 97	4572	N/A	125

5.7 Structural Capacity

The function of the pavement structure is to effectively carry traffic and transfer wheel loads to the roadbed soils. Structural testing is the evaluation of the load carrying capacity of the existing pavement subsoils.

Structural data is not routinely collected for pavement monitoring by most agencies. Surface deflection data is mainly used for selecting and designing specific rehabilitation strategies for pavement sections under consideration. Exact location and frequency of structural testing within specified road sections should be carefully determined prior to seeking testing services. The tests should be limited to locations where distress and roughness surveys indicate structural problems and areas where overlays are anticipated. The results of these tests reflect the degree of structural adequacy that exists in the pavement structure.

Although expensive, structural testing can considerably reduce maintenance and rehabilitation costs. Many agencies use minimum or standard thickness for overlays. Thus, if a 50 mm (2-inch) overlay is the standard design and structural testing indicates that a 40 mm (1.5 inch) overlay will provide adequate strength, a saving of approximately 20 percent is realized. Structural testing can also determine the need for varying overlay thickness within a single project, thereby realizing considerable savings. For even a small project, reduced material costs easily justify the cost of structural testing.

On the other hand, an inadequate standard design can be even more costly. Nothing undermines support of a highway agency more quickly than a pavement which fails soon after construction.

The same considerations apply to aggregate surfaces. The cost of maintaining aggregate surfaces in rural areas can be a significant portion of total maintenance funds. Proper design results in one-time construction and eliminates the costly addition of aggregate at regular intervals.

Structural evaluation includes both destructive and nondestructive testing. Destructive testing involves coring and removing surface, base, and subsoil samples for laboratory testing to determine the load carrying capacity of the roadway. Another destructive procedure involves the excavation of pits for tests such as on-site plate bearing or field CBR (California Bearing Ratio). Samples of pavement layers and supporting soils are retrieved and tested in the laboratory to determine layer properties. The strength of the materials and types of damage present in each layer, are used to determine the load carrying capacity, the damaged layers, and the cause of structural failure. This information can then be used in a design and analysis procedure to determine whether the pavement is structurally adequate for current and projected traffic loadings *(1,3,15).*

Non-destructive testing (NDT) can also be used to evaluate the structural adequacy and load-carrying capacity of an existing pavement. NDT provides measurements of the overall pavement response to an external force or load without disturbing or destroying the pavement components *(16).* NDT has many advantages over the destructive testing methods including:

- It provides in-situ properties of the pavement conditions
- It does not damage the pavement
- It minimizes laboratory tests
- It is fast

The application of loads on a pavement surface includes strains **(**ε) in the underlying layers causing stresses in all layers. The summation of all vertical strains in the pavement structure and in the underlying sub-grade represents the surface deflection **(**δ) of the pavement. The deflection value is considered an excellent indicator of pavement strength; in other words, once deflection exceeds a certain limit, the pavement is certain to show some kind of structural weakness. Thus, a weaker pavement will deflect much more than a stronger pavement at a given load.

A number of non-destructive testing devices have been developed in recent years and are being used in the pavement structural evaluation analysis. All of these NDT devices provide some measure of surface deflection of in-service pavements in response to an external load.

The non-destructive testing devices which are available in the United States to evaluate the in-situ properties of pavements are *(16):*

1. Benkelman Beam,
2. Dynaflect,
3. Road Rater, and
4. Falling Weight Deflectometer (FWD).
5. Rolling Deflectometer
6. Ground Penetrating Radar (GPR)

The first five devices operate by measuring the pavement response to an imposed force. The response is generally in terms of surface deflections at one or more points on the pavement. Major differences between these devices include the load levels, the way the load is applied to the pavement, and the number of points at which deflections are measured. A device that applies a static or slowly moving load is the Benkelman beam. The common devices that apply a vibratory steady state load to the pavement surface are the Dynaflect and the Road Rater. The device that uses an impulse loading is the Falling Weight Deflectometers (FWD). The rolling deflectometer is still under development in the United States.

Benkelman Beam: This device is generally used to measure the rebound deflection of the pavement surface under a static or slowly moving single axle, double wheel load. An 8-foot-long (2.4 m) probe is placed between the dual tires [11.00 x 22.5, 12-ply and 70 psi pressure] of a truck which carries an 18,000 pounds (8,200 kg) single axle load. As the pavement is depressed, the beam pivots around a point of rotation on the reference beam which rests on the pavement behind the area of influence, so that the back extension of the beam depresses an Ames dial which records maximum deflection to within 0.001 inch (0.025 mm). While this device is limited to measurements of total deflection of a vehicle operating at creep speed, it has the very important advantages of simplicity, versatility, and rapidity of measurements *(3,16).*

Dynaflect: This device is an electro-mechanical device consisting of a dynamic force generator based on counter rotating fly wheels, and of five velocity transducers for sensing deflection mounted on a trailer. This device places a 1,000 pound (454 kg) peak to peak vibratory load on the pavement surface through two rubber covered steel wheels *(3,16).* The deflections are measured between the two loading wheels with velocity transducers and generally at 12 inch (0.3m) intervals from that point.

Road Rater: The Road Rater is also a steady state vibratory device which is trailer mounted and can be towed by a vehicle capable of pulling the trailer weight. Older models were mounted on the front of a vehicle. The maximum rated static loads are 2400 lbs., 3800 lbs., and 5800 lbs. for the models 400 B, 2000, and 2008 respectively. The load is applied to the pavement surface through a steel loading plate. The standard loading plates are 4 x 7 (102 x 178 mm) steel pads with a 5.5 inch (14 mm) center gap for model 400 B and a 12 inch (300 mm) diameter circular plate for the model 2000 and 2008. The dynamic force generator uses a lead-filled steel mass which is accelerated up and down by a servo-controlled hydraulic actuator. Both the amplitude and frequency can be changed by the operator. This allows different dynamic peak-to-peak rated loadings of 500 to 3000 lbs. for the model 400 B, 1000 to 5500 lbs. for the model 2000, and 1200 to 8000 lbs. for the model 2008. The force is measured with a strain gauge-type force transducer in most models. The loading frequency can be varied continuously from 5 to 70 cycles per second at 0.1 cycle per second increments with the normal working range in the 10 to 60 cycles per second range. The deflection is measured using at least four velocity transducers located in the center of the loaded area and general at 12 inch (0.3) intervals from that point *(3,16).*

FALLING WEIGHT DEFLECTOMETER (FWD): The Falling Weight Deflectometer is an impulse deflection device that lifts a weight to a given height on a guide system and then drops it. The falling weight strikes a specially designed plate, transmitting the impulse force to the pavement to produce a half-sine wave load pulse that approximates that of an actual wheel load. The magnitude of the load can be varied from 1,500 to 24,00 pounds (680 to 10,886 kg) on devices commonly used on roads and streets by changing drop height and the amount of weight. The load is transmitted to a 11.8 inch (300 mm) diameter load plate, and a strain type transducer measures the magnitude of the load. Deflections are measured using up to seven velocity transducers or linear variable distance transducers that are mounted on a bar and automatically lowered to the pavement surface with the loading plate. One transducer is placed in the center of the loading plate with the others placed at intervals up to 7.4 feet (2.25 m) from the first. It is a trailer mounted system *(3,16).*

The two primary NDT methods are vibratory and falling weight. Although both devices produce useful analyses of low-volume pavement structures, the falling weight deflectometer more closely approximates a heavy moving wheel load. Falling weight deflectometers induce a heavy enough load to yield meaningful results in rigid pavements. Nondestructive testing analysis requires knowledge of the existing pavement structure in terms of layer types and thickness. Coring of pavements may be necessary to support the analysis of NDT data. An NDT analysis will typically result in an evaluation of remaining service life of a pavement in terms of 18-kip equivalent single axle loads (ESALs), and an overlay thickness design.

ROLLING DEFLECTOMETER: The FHWA initiated a Small Business Innovative Research (SBIR) contract with Applied Research Associates (ARA), Inc. in 1996 to develop a rolling wheel deflectometer (RWD) for structural assessment of pavements. Phase I of the SBIR has been completed and Phase II has been initiated. Phase I research identified magnitudes of deflections (maximum values and basin offset values). The objective of the Phase II research is to develop a prototype RWD that is suitable for network level analysis in PMS applications. The RWD will collect data at highway speeds of 50 mph operating within traffic streams. A prototype RWD has also been developed independently by Quest Integrated Inc. and Dynatest. The primary data collected with an RWD will be deflection magnitudes and the shape and size of deflection basins.

This presents a concern as to the best location to collect deflection data. The basin trailing the wheel is the longest, and that transverse is the shortest, with that ahead of the wheel being slightly less than that behind. The leading side represents the loading side and the trailing side represents the unloading response. Most of the historical data primarily measured the trailing portion of the basin due to convenience in measurement. However, for RWD applications, the leading portion of the basin is more convenient because comparisons are made to the undeflected pavement ahead of the load wheel. Additionally, the leading part of the basin may be less influenced by hysteresis effects. Both RWDs will collect deflection data, wheel load, pavement temperature, and travel speed (nominally 50 mph). In their FHWA Study ASA has proposed that the RWD data be processed in real-time to produce the pavement structural index. The data to be stored would only be the maximum deflection, structural index, pavement temperature, station numbers, data and time of the day. Although measurements are to be made continuously at 1-foot increments, the stored data will be for increments of 200 feet up to 1,000 feet, as determined by the operator. Using these increments will avoid excessive data storage requirements; all other data will be purged by the system and overwritten with new data.

Potential RWD Input into a PMS

In ARA's Phase I Study, they indicated concern for the large amount of data that could be created by a RWD. Potentially the RWD could produce a set of deflection measurements for every meter of highway. They proposed to use the deflection and load data to determine the effective structural number using the Burmeister's two-layer solution to determine the effective modulus for all pavement layers. ASA proposed using the same procedure that is used for the deflection based overlay design procedure developed in the 1993 AASHTO Guide for the Design of Pavement Structures to estimate the remaining service life. *(28)* The remaining structural service life would be determined by comparing the required design structural number to the existing effective structural number. The resulting remaining service life would be given in terms of a Structural Index which would be the Log of the remaining design Equivalent Single Axle Loads determined from the AASHTO design formula.

A somewhat similar approach was used is a special study to determine the project scopes in New Jersey's PMS. *(29)* In the New Jersey Study the authors also used the AASHTO deflection based overlay design procedure to determine the Effective Structural Number , but then compared it to the Required SN for a normal design procedure to determine the overlay thickness required for each section of pavement tested. Here they used standard FWD testing at a test spacing of about 10 tests per kilometer of highway.

Cost Comparison

The New Jersey Study provides a good basis for a cost comparison of the potential advantage of using a RWD to collect and process structural response for a PMS. Currently it cost about $1,000 per day to run a standard FWD. With a reasonably productive measuring procedure, the FWD could perform 10 tests per kilometer over a distance of 15 to 20 kilometers per day. Since the FWD requires stopping on the travel pavement for every test, a traffic control crew is also required. Thus the total cost of FWD testing is about $2,500 per day. If the production rate is about 20 kilometer per day the total cost of FWD testing is over $100 per kilometer. Using a RWD, the production rate would be more in the order of 300 kilometers per day. Since RWD are still in the prototype development stage it is difficult to estimate what the actual operating cost will be. If they are say five times the current rate for FWDs which would be about $5,000 per day, the much higher production rate of the RWD would bring down the structural survey cost to less than $20 per kilometer.

5.8 Roughness

Pavement roughness measurements indicate whether irregularities in the roadway surface which adversely affect the ride of a passenger in a vehicle are present. Roughness is not only an important distress type itself but is also an indicator of other distress and can be used to prioritize visual distress surveys. Roughness evaluation measures the rideability of the pavement.

Pavement roughness is important for many reasons. Two of the most important are:

1. Public Perception – Roughness is the <u>primary criteria</u> by which the public judges the ability of a highway agency to maintain not only its pavements, but its entire highway network.

2. Pavement Performance – Roughness leads to more rapid deterioration of pavement structures. Some amplitude-wavelength combinations can cause dynamic forces of 50% - 100% in excess of static weights.

Serviceability Concept: Until a measure of pavement serviceability was developed in conjunction with the AASHO Road Test, little attention was paid to the concept of highway performance or condition measured over time. A pavement was either satisfactory or unsatisfactory. The idea of "relative" performance was not well developed. Most pavement design concepts did not consider the level of performance desired, and design engineers had varied definitions of performance.

Results of the AASHO Road Test provided a badly needed method of pavement performance evaluation known as the "*serviceability performance concept*." The evaluation of serviceability and performance depends on the interaction of three components: the pavement user, the vehicle, and the pavement itself. The serviceability scoring system measures the subjective reaction of a group of roadway users. The serviceability concept is based upon the following assumptions:

§ Highways are for the comfort and convenience of the traveling public.

§ Users' opinions as to how they are being served by highways is largely subjective.

§ Characteristics of various pavements can be measured objectively and then related to the users' subjective evaluation.

- Serviceability can be measured by the average evaluation of all highway users. Differences of opinions preclude the use of a single evaluation when rating serviceability. The average evaluation of all users, however, is a good measure of serviceability.
- Performance is assumed to be an appraisal of the serviceability history of a pavement. The performance of a pavement can be described as serviceability observed over time.

The Serviceability Index was developed for the AASHO Road Test based on the above assumptions. The index is a 0 to 5 rating which can be determined by a panel rating, (using the average of all panel members' subjective evaluations), or by a mechanical roughness measuring device that correlates measured roughness to an average panel rating. Values based on panel ratings are known as Present Serviceability Ratings (PSR) and correlated mechanical measurements are known as Present Serviceability Indexes (PSI). A PSI is simply a mechanical estimate of the user's subjective evaluation of ride quality.

OTHER ROUGHNESS STATISTICS: Since the AASHO Road Test, many other statistics have been developed to quantify roughness levels on road surfaces. Many of these measures are summary statistics derived from precise measurements of road profile. Once a roughness meter is calibrated to one of these profile-based statistics, then the direct output of a roughness meter can be converted to the standardized roughness statistic. The most widely accepted roughness statistic is called the International Roughness Index (IRI). Other similar statistics include the Quarter Car Index (QI) and the standard Mays Meter number (MO). All of these statistics are similar in derivation in that they are initially obtained by a mathematical manipulation of the surface profile. Because of this, they are a more objective measure of roughness than the serviceability index and present serviceability ratings which are basically subjective.

Sayers *(17)* has compiled a thorough summary and discussion on the development of the IRI. The IRI evolved over many years, in three stages:

1. Quarter-car simulation on high-speed profilers. Routine analysis of road profiles began shortly after the General Motors (GM) profilometer was developed in the late 1960s. Like high-speed profilers today, it could measure true profile over a range of wavelengths affecting vehicle vibrations. One of the first research applications for this type of system combined measured road profiles with a quarter-car computer model that replicated the Bureau of Public Roads (BPR) Roughometer, a one-wheeled trailer with a road meter. GM licensed K.J. Law, Inc. to market the device commercially and continue its development. A commercial version was soon available that included a quarter-car analysis to summarize roughness of the measured profiles. Users of early K.J. Law profilometers could choose between two quarter-car data sets: one for the BPR Roughometer and one for a 1968 Chevrolet Impala.

2. NCHRP research and the Golden Car. In the late 1970s, NCHRP sponsored a study of response-type road roughness measuring systems such as the BPR Roughometer and vehicles equipped with Mays ride meters. The results were published in *NCHRP Report 228 (18)*. An objective of the study was to

   develop calibration methods for the response-type systems. The researchers, Gillespie and Sayers, concluded that the only valid methods was *calibration by* *correlation* against a defined roughness index. The best correlation was obtained by using a vehicle simulation with a set of parameter values that is often called the *Golden Car*. (The name is based on the concept of a golden reference instrument kept in a vault and used to calibrate other instruments).

The NCHRP study provided a standard quarter-car model, and users of K.J. Law profilometers soon had access to an analysis called *Mays simulation*, which used the Golden Car data set.

3. The World Bank development of IRI. In 1982, the World Bank initiated a correlation experiment in Brazil called the International Road Roughness Experiment (IRRE) to establish correlation and a calibration standard for roughness measurements. In processing the data, it became clear that nearly all roughness-measuring instruments in use throughout the world were capable of producing measures on the same scale, if that same scale had been selected suitably. Accordingly, an objective was added to the research program: develop the IRI.

   The main criteria in designing the IRI were that it be relevant, transportable, and stable with time. To ensure transportability, it had to be measurable with a wide range of equipment, including response-type systems. To be stable with time, it had to be defined as a mathematical transform of a measured profile. The Golden Car simulation from the NCHRP project was one of the candidate references considered, under the condition that a standard simulation speed would be needed to use it for the IRI. The quarter-car was selected for the IRI because it could be used with all profiling methods that were in use at that time. The consensus of the researchers and participants is that the standard speed should be 80 km/hr (49.7 mph) because at that simulated speed, the IRI is sensitive to the sample profile wavelengths that cause vehicle vibrations in normal highway use.

The World Bank *(19)* defined two classes of profiling methods that were later adopted by the FHWA for the HPMS data base. Profilers are considered Class 2 if they produce IRI measures that are neither high nor low on the average. However, an individual measurement is expected to have random error. Some profilers clearly are more accurate than others, so the concept of a Class 1 measurement was introduced to define a reference that can be used to determine the accuracy of other instruments. A Class 1 instrument must be so accurate that the random error is negligible: its IRI measure is "the truth."

When the IRI was defined in the World Bank Technical Report, there were only about a half-dozen inertial profilometers in America. Since then profiling has become the primary means for measuring road roughness in the United States. More than half the states have purchased or built profiling systems. The federal government maintains a fleet of profilers for calibration and research programs, and consulting companies maintain profiling systems to provide measures to states and local districts that do not have their own equipment. FHWA has encouraged profiler use and has sponsored several correlation experiments. Profiler users have organized into the Road Profiler

User Group, which has established an annual correlation experiment for several years in which users are invited to measure profiles and IRI for test sites.

The profilers in use cover a wide variety of sensor types, cost, and analysis options. Limited by the speed of sound, systems with ultrasonic sensors can measure profile at intervals no closer than 300 mm (1 ft) at highway speeds. Other systems, with laser sensors, can measure at intervals going down to a few millimeters. Some systems perform minimal profile filtering. Others routinely smooth the data to avoid aliasing and remove long wavelengths to standardize plot appearances. Even with these differences, most profilers in use can obtain IRI measures that show reasonable agreement (within 5 percent).

However, recent correlation experiments show that no existing profiler can measure “true IRI” with the high accuracy one might expect of a Class 1 instrument (i.e., within 2 percent). Further research is needed to determine the reasons that consistent measures of roughness are not obtained. Two possible sources of discrepancy are user practice and changes in road profile due to temperature and environmental effects.

The following points fully define the IRI concept:

1. IRI is computed from a single longitudinal profile. The sample interval should be no larger than 300 mm for accurate calculations. The required resolution depends on the roughness level, with finer resolution being needed for smooth roads. A resolution of 0.5 mm is suitable for all conditions.

2. The profile is assumed to have a constant slope between sampled elevation points.

3. The profile is smoothed with a moving average whose base length is 250 mm.

4. The smoothed profile is filtered using a quarter-car simulation, with specific parameter values (Golden Car), at a simulated speed of 80 km/hr (49.7 mph).

5. The simulated suspension motion is linearly accumulated and divided by the length of the profile to yield IRI. Thus, IRI has units of slope, such as inches per mile or meters per kilometer.

ROUGHNESS MEASURING EQUIPMENT: Equipment for roughness survey data collection may be categorized in 4 primary categories:

1. Rod and Level Survey, and the Dipstick Profiler
2. Profilographs
3. Response Type Road Roughness Meters (RTRRMs), and
4. Profiling Devices

Rod and Level: Surveying instruments can be used to determine the accurate profile of a road at any desired spacing. However, this requires normal rod and level measurements which are time consuming and require closing the road during the survey.

Dipstick Profiler: A first-step automation of the rod and level survey is by profile measurement with the Dipstick .

The Dipstick consists of an inclinometer in a case supported by two legs separated by 12 inches. Two digital displays are provided, one at each end of the instrument. Each display reads the elevation of the leg at its end relative to the elevation of the other leg. The operator then “walks” the Dipstick down a premarked pavement section by alternately pivoting the instrument about each leg. Ten to 15 readings per minute are recorded sequentially as the operator traverses the section. Software analysis provides a profile accurate to plus or minus 0.005 inch.

The most prevalent use of the device has been for manually profiling roughness calibration sections for the calibration of RTRRMs. Two versions of the device have been developed. Special care must also be taken to ensure that the Dipstick feet do not change location, destroying the reference elevation during the survey. The manufacturer has developed rubber boots to help maintain contact on certain aggregates in paved surfaces.

Profilographs: The most common device to monitor construction quality control on Portland cement concrete pavements is the profilograph. Profilographs have been available for many years and exist in a variety of forms, configurations, and brands. Due to their design and low-speed operation (walking speed), they are not suitable for condition surveys. Profilographs should never be used to calibrate other roughness data collection equipment.

Response Type Road Roughness Meters (RTRRMs): Road meters or RTRRMs collected the bulk of pavement roughness data from 1940 through the late 1980s. Two very serious limitations, however, have helped speed the movement away from the RTRRMs:

1. Profile Measurement – RTRRMs <u>cannot</u> measure pavement profile. They record the dynamic response of the mechanical system travelling over a pavement at a constant speed. The characteristics of the mechanical system and the travelling speed affect the data.

2. Calibration – In order to provide accurate, consistent, and repeatable data, the devices must be frequently calibrated through a range of operating speeds, against sections of known profile. The cost of this activity is high.

Due to the limitations and the development and nationwide use of low-cost profiling devices, the RTRRMs are not used much today - except to correlate existing roughness databases to the new profiling devices. In a few years, the RTRRMs will be used very little, if at all.

This equipment is easy to use, relatively inexpensive, and can be operated at speed close to normal traffic speed. Several types of devices are available, but the May’s Ride Meter will be presented for information.

The May's Ride Meter (MRM) provides roughness measurements proportional to the vertical distance changes between the vehicle body and its rear axle as the vehicle travels over a pavement. The primary advantages of the MRM include initial cost, ease of operation, and the roughness record provided. However, the vehicle must travel at a constant speed for at least one-tenth mile (0.16 km) long sections, which is often difficult in city streets. In addition, the MRM must be calibrated frequently to ensure that reasonable accuracy in measurements is achieved *(3)*.

Profiling Devices: Profiling devices provide accurate, scaled, and complete reproductions of the pavement profile within a certain range. They eliminate the time consuming, labor intensive calibration process necessary to collect reliable data with response type road roughness systems and can also be used to calibrate RTRRMs. Today, most agencies use the inertial reference systems for measuring pavement profile. The devices measure, compute, and store the profile through the creation of an inertial reference by using one or two accelerometers on the body of the vehicle to measure the body vertical motion in one or both wheelpaths. The relative displacement between the accelerometer and the pavement surface is measured with an acoustic, optical or laser sensor. A summary of the process is as follows:

1. *Accelerometer* – Measures the vertical displacement of the vehicle as a function of time.

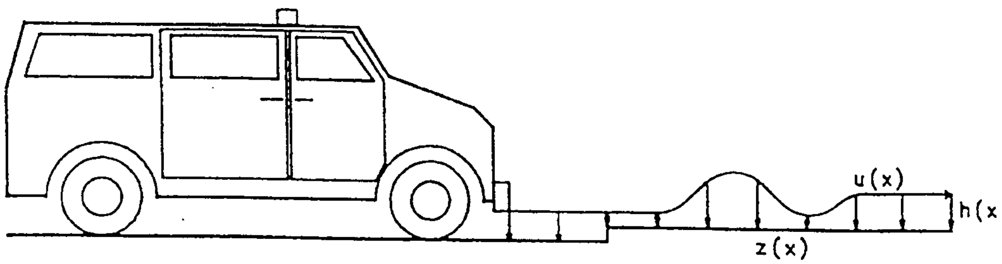
2. *Distance Measuring Instrument* – Measures the horizontal distance of vehicle travel.

3. *Sensor* – Measures the vehicle's height above the roadway surface at equally spaced intervals of distance.

4. *On-board Computer System* – Synchronizes subtraction of the vehicle displacement and height measurements to compute the relative profile, stores the computed profile, and reconstructs a filtered profile from the stored profile. Figure 5.19 illustrates the process.

The states have moved rapidly from RTRRMs that collected pavement response data, to profiling devices that measure pavement profile. Most of these devices include software analysis packages that can calculate any of the previous roughness indices computed from the response data as well as pavement profiles, filtered at varying cutoff lengths. Profiling has greatly improved the analysis of pavement condition, and provides clues to engineering rehabilitation and maintenance strategies that were not possibly to develop from the RTRRM data. Several states already develop strategies using profile data or profile data in conjunction with distress data.

Figure 5.19 The Inertial Reference Principle



h(x) - Vehicle Height above Pavement
u(x) - Vehicle Position
z(x) - Vertical Road Profile

***Pavement Profile* = z(x) = u(x) – h(x)**

The K.J. Law 690 DNC profilometer uses the inertial reference principle to measure profiles in both wheelpaths. Relative displacement between the accelerometers and the pavement surface is measured with a highly accurate non-contact light beam measuring system. Differential pavement elevation is determined using the principle of triangulation. Profile computations are performed at six inch intervals in real time as the device traverses the pavement section. One inch data points are measured and averaged over a 12” interval and recorded as profile every six inches of travel. Vertical resolution is 0.01 inch. The operator may select wavelengths for filtering, which do not change during vehicle speed alteration. The device simulates the Mays, PCA roadmeter, and BPR Roughometer indices, and computes PSI values from a mathematical model using a comparison to a panel roughness rating.

Until a few years ago, sophisticated road profiling equipment was extremely expensive. This is not so today. In 1981, the South Dakota Department of Transportation (SDDOT) designed and constructed a low-cost Road Profiler. Between 1982 and 1986 SDDOT enhanced the Road Profiler’s capabilities and added two additional sensors to estimate rut depth. The current Road Profiler collects pavement condition data at highway speeds, surveying about seven hundred miles of pavement during a forty-hour work week. The Road Profiler software allows data reporting in various forms-filtered profiles, roughness ratings, and power spectral density. The SDDOT has shared the Road Profiler technology and provided technical assistance to other State highway agencies (SHAs) interested in procuring a similar device. About 25-30 other SHAs have indicated an interest in the system. Twenty-four have now fabricated replicate units, either in-house or through an equipment vendor or plan to do so in the near future.

Interested States have formed a User’s Group and participated in meetings during 1989 to 1990 to provide technical information about the device, share information about system enhancements, evaluate the capability of the units, and make future technological innovations available to the users. One of the Road Profiler's advantages is its comparatively low initial and operating costs. A system may be assembled for about $50,000, including the van. Operating costs have been very low, on the order of $2.00 per lane mile in South Dakota. Pennsylvania has reported data collection costs of about $5.00 to $6.00 per lane mile. Roughness data can be reported in International Roughness Index units, satisfying FHWA 1989 Highway Performance Monitoring System requirements to report roughness data in this form. The wide-spread use of the Road Profiler will eventually lead to a much-improved assessment of the HPMS pavement roughness reporting requirements, and will ultimately revise them due to the rapid, nearly universal practice of collecting pavement profile, not response data.

Side by side tests comparing home-built and commercially manufactured units were conducted during the two User's Group meetings in Pierre, South Dakota in November 1989, and Cheyenne, Wyoming in September 1990. The test results were compared with manual profiles and comparisons were made between devices. The level of precision and repeatability of each device was also assessed in terms of comparability with manual profile, comparability among devices, level of precision, accuracy, and repeatability. Future User Group meetings have been planned. Continued enhancements to the Road Profiler hardware and software are anticipated. Some have already occurred. For example, several states have purchased an IBM-PC based system to correspond more directly with their own departments IBM-based computer databases.

5.9 Skid Resistance (Surface Friction)

Skid resistance measurements of highways, roads, and streets, are generally for safety analysis and on locations where accidents are suspected of being caused by deficiencies in surface skid resistance. Specialized equipment frequently used to measure surface friction can be categorized as portable field devices and trailer devices.

Trailer Devices: Generally, these devices consist of a trailer towed, usually at 40 mph, over the dry pavement with water applied to the pavement ahead of the test tire. The most common trailers under this class of equipment used in the US includes the Locked-Wheel-Trailer and Yaw Mode. These devices are generally most applicable for skid measurements on straight sections of through roads. They are difficult to use on many city streets.

Locked Wheel Mode: A trailer is towed, normally at 40 mph. Water is applied in front of the test wheels, and the test wheels are locked. The force required to drag a tire that is prevented from rolling over the wet pavement is measured after the test wheel has been sliding on the pavement for a certain distance (i.e., after the temperature has been stabilized). A skid number (SN), where: SN = 100 x Friction Factor is calculated for that part of the pavement. Skid number is the standard procedure for evaluating the coefficient of friction between a tire and pavement. A standard bias-ply 7.5 x 14 tire (ASTM E534) is specified to eliminate tire type and design as variables in the measurement of skid resistance. The skid number calculated by this method is dependent on temperature, and because of the complex relationship between air, water, pavement, and tire, no satisfactory method has been developed for correcting the skid number for temperature *(3)*.

Yaw Mode: The test wheel (unbraked) is directed at an angle from the direction of motion and the sideways friction factor is measured. At some Yaw angle, the side force peaks. Since the critical Yaw angle is subject to many variables, there is controversy concerning which constant Yaw angle the wheels should be set at during testing. An angle should be used that is relatively insensitive to differences in surface characteristics and operating conditions *(3)*.

The Mu-Meter, developed in England, is a fairly simple version of a Yaw mode device. The Mu-Meter is a three-wheeled towed trailer in which two friction-measuring wheels and a rear wheel are mounted on a triangular frame. The two smooth outer wheels are set at an angle of 7 ½ degrees from the line of travel. A rear, middle wheel measures the distance of travel and holds the trailer on a stable course. By use of a simple load cell and the recorder, distance and the coefficient of friction are recorded as friction is encountered on the pavement. The speed of the test wheel ranges from 40 mph to 100 mph. A water delivery system is available to distribute water in front of the two wheels that measure friction.

Automated procedures to measure pavement friction have been available since the 1940's. The locked wheel friction tester has been, and remains the work horse data collection unit.

Table 5.13 summarizes past, present, and projected future friction measuring equipment trends.

Table 5.13 Friction Equipment Trends

DEVICE	NO. MID '80s	NO. 1990	NO. MID '90s
Locked Wheel Tester	38	41	35-45
Mu-Meter	4	2	0-2
Spin-Up Tester	0	0	0-10?
Laser or Image Processing	0	0	0-20?

New methods to improve testing efficiency and reduce skid testing costs and device wear and tear are underway. Recent studies indicate that the spin-up tester may produce accurate results at lower costs. Like the locked wheel tester, the device is trailer mounted. Testing begins following the locking of the wheels and continues after the release of the brake until the wheels reach full angular velocity. The time interval between the moment the brake is released and the achievement of full angular velocity is indicative of the pavement surface friction.

Developmental efforts to correlate pavement surface texture to a locked wheel skid number are ongoing with both video systems and laser devices. The University of New South Wales (Australia) has developed the Yandell Mee Friction Tester which correlates skid resistance and texture depth to both sideways force and the locked wheel modes. The device uses a video camera, tracking device, and image enhancement to capture an enlarged video picture of the pavement surface. An on board computer collects the data. Software performs a statistical analysis of the texture, and produces output data on the friction factors. The vehicle must be stopped to conduct the 30-second test. Results are processed in real time to provide the skid numbers at various vehicle velocities.

The Laser RST and other equipment measures pavement macrotexture at highway speeds using 32 kHz lasers. The device cannot however, measure pavement microtexture, which also has some influence on skid resistance. Development of 64 kHz lasers for this purpose and for travelling deflection measurement is ongoing.

Portable Field Devices: Several portable field devices have been developed to measure skid resistance. Some of these devices include the Keystone Tester and the California Skid Tester. These devices are most suitable for measuring friction on city roads and streets and can be useful in measuring skid resistance on the approaches to a stop sign or a traffic signal and in similar locations where accident frequencies are usually high.

The Keystone Tester: A hand carried device that employs a rubber shoe that slides along the pavement as the operator "walks" the tester. The frictional resistance experienced by the shoe is converted to hydraulic pressure and displayed on a gauge. Water must be applied to the pavement ahead of the tester when water accidents are considered *(17)*.

The California Skid Tester: It operates on the principle of spinning a rubber-tire wheel while it is off the ground, lowering it to the pavement, and noting the distance it travels against the resistance of a spring before it stops. This device is attached to the rear of a suitable vehicle, which is stationary during a test. This tester is normally operated with glycerine instead of water as the pavement lubricant, because glycerine ensures a longer lasting, and more uniform film *(20)*.

These Portable Testers are relatively inexpensive. They also permit friction to be measured in locations where a trailer tester cannot operate. However, they are generally considered less accurate than the trailer testing devices.

Interpreting Friction Testing: Most agencies use a skid number to indicate the level of surface friction on a pavement surface. As this number decreases, the surface friction decreases. Low numbers should indicate greater potential for accidents, especially in wet weather.

5.10 Aggregate Surface Roads

Aggregate surfaces can be completely integrated into a surface management program. However, special considerations should be made for these roads.

The maintenance of unbound surfaces is an important concern usually to local governments in rural areas, although federal agencies such as the Bureau of Indian Affairs and the Forest Service also own and manage large unsurfaced road networks.

Keeping these roads passable under adverse weather conditions requires a substantial portion of maintenance funds. Approximately half of the road mileage in the U.S. consists of unpaved surfaces. Although these roads carry small portions of the total traffic volume, they remain a vital aspect of the economy because they provide land access and service for agricultural needs.

The term “unpaved” is misleading. Most, if not all, unpaved roads consist of a stabilized surface. Whether existing materials are used or additional materials added, the resulting all-weather surface is actually an unbound pavement and must be treated as such..

Unbound surfaces are much more dynamic than bound pavements and their condition can deteriorate rapidly. However, routine maintenance procedures improve conditions just as rapidly. Maintenance must be performed more frequently than for paved or bound surfaces.

Condition Assessment of Aggregate Testing: The important condition factors in aggregate surfaces are: roughness or corrugation, dust generation, drainage, rutting, gravel loss and potholes. Each of these factors are discussed below:

- Roughness – When evaluating roughness on aggregate surface different criteria must be used than for pavements. A higher level of roughness can be tolerated than on surfaced roads. The most important roughness distress is corrugation. Corrugation is caused by a loss of fines in the surface gravel due to dust generation or washing. Corrugation can be corrected by reblading or, when severe, by applying new gravel and reblading.

- Dust Generation – Dust from unpaved roads can be a nuisance to property owners, a potential safety problem, and a cause of environmental damage. It results in a loss of fines in the surface gravel, as explained above. When evaluating dust generation, characteristics of adjacent property and slight distance requirements must be considered. Some locations tolerate more dust than others. Dust generation can be controlled by various methods of surface stabilization, such as liquid asphalt spray or liquid calcium chloride.

- Drainage – The crown of an aggregate road is subject to change. The adequacy of the crown should be considered when evaluating the condition of unpaved surfaces. The uniformity of the crown cross-slope is very important. When unpaved surfaces are not properly bladed, a “secondary ditch” appears at the edge of the roadway. This secondary ditch intercepts drainage and channels it to the traveled way rather than allowing it to cross the shoulder and enter the constructed ditch. Proper blading techniques maintain a proper crown and prevent development of secondary ditches. Full width blading may be necessary to maintain shoulders and adequate ditches.

- Rutting – Rutting in the wheel paths is common in unpaved surfaces. Rutting interrupts cross drainage and creates safety problems. As with roughness, criteria for evaluating rutting must take into account the nature of unpaved surfaces. There are two causes of rutting. It can be caused by repeated tire action on the cover gravel, resulting in the displacement of the gravel. More seriously, rutting can be a structural problem resulting in plastic deformation of the base material. Rutting is corrected by regrading, unless it is the result of structural problems in the base. An inadequate base must be corrected by reconstruction and good compaction.

- Gravel loss – Unbound surfaces with gravel cover lose material over time due to the action of traffic. This is particularly true if the surface material has a low plasticity. Gravel loss is more severe on roads that have higher traffic volumes, heavier truck loadings, steep grades, and frequent turns and curves. Gravel loss is corrected by regraveling and reblading. Excessive gravel loss might justify a stabilization treatment.

- Potholes – Potholes develop rapidly in unpaved surfaces as a result of poor drainage, traffic action, loss of cover gravel and weaknesses in the base. Deep and extensive potholes might require localized base reconstruction and recompaction. Less severe potholes can be corrected by reblading.

5.11 Drainage Surveys

Poor drainage causes poor pavement performance. Water allowed to pond on the pavement surface creates a hazard to motorists, saturates the subgrade soil, an causes deterioration of the pavement. Ditches which are allowed to silt in and collect debris provide poor drainage. Moisture then becomes trapped in the subgrade or base with pavement failure a likely result.

Pavement failure within the design life is caused by two main factors: load and moisture. Load capacity can be increased by an overlay. A moisture related distress indicates a drainage problem in the base or subgrade. If proper drainage of each pavement element is not provided during rehabilitation, the same moisture related distress will recur.

The survey team should be instructed to identify surface drainage problems. High shoulders can cause ponding of water on the pavement surface and erosion along the pavement edge. Debris can block storm sewer inlets and cause flooding of the roadway. Correction of these deflects can then be scheduled.

Other signs of deficient surface drainage which may be detected during a visual survey are:

- Standing water in ditchlines.
- Concentrating weed growth indicating saturated soil in ditchline or at edge of pavement.
- Evidence of water ponding on the shoulder.
- Deteriorated joint or crack sealants.
- Any evidence of pumping.

Additional drainage problems may not be so obvious. Subsurface drainage depends upon material properties of the subgrade soil. Pavement distress may be the only outward indication of a saturated subgrade soil or base. The recognition of the mechanisms causing such distress is necessary to choose the appropriate rehabilitation procedure. Tables 5.2 and 5.3 summarize the causes of distress in asphalt and concrete surfaces.

5.12 Deciding How Much Data to Collect

To support network-level analysis, sampling processes can be used to reduce data collection costs *(1).* Sampling is conducted by measuring information about a part of the whole that can be used to estimate something about the whole *(21).* Standard sampling techniques are used to avoid collecting “unrepresentative” data that could bias the estimates *(21,22,23).*

Sampling can be conducted on a network or section basis. To estimate the condition of the network for planning purposes, only a sample of the system needs to be surveyed for each measure selected to be used, e.g., only a portion of the data collection or management section will need to be surveyed. However, if individual sections are to be identified as needing maintenance or rehabilitation in the PMS, then the condition of each section must be known, e.g., each section must be surveyed but only a portion of each section can be surveyed.

Network Sampling: Studies conducted about the sampling of condition based on distress have generally been based on collecting information to predict a condition index. In two such studies, the pavement evaluation score (PES) used by the Texas Department of Transportation (TxDOT) were considered in addition to serviceability index based on roughness and surface curvature index based on Dynaflect measurements *(24,25)*. The results were considered adequate to represent conditions on a state-wide basis and for district stratification of the statewide network.

All sampling studies indicate that a smaller percentage of the samples will need to be inspected when the total number in the whole increases. This generally leads to the conclusion that a greater percentage of arterial roads and streets will need to be inspected than for residential and local roads and streets. References 22 and 23 give detailed instructions on selecting sample sizes for different conditions. The TxDOT studies found that a sample size of 2 to 5 percent, depending on the size of the network being sampled, will be adequate to determine average condition *(24)*. If the goal is to predict the distribution of condition so that the percent of the network below some selected score can be identified, then a sample size of 10 to 15% was needed *(25)*. If the goal is to predict the cost to repair those sections of pavement below some selected value, a sample size of 30 to 35 percent is needed *(25)*. This approach will support overall planning concepts. Many states survey the first 500 feet of a mile, which corresponds to approximately 10%.

Section Sampling: If a goal of the PMS is to identify those sections of pavement that are in a selected condition level that requires some specified treatment, the condition of each section must be defined. However, this does not mean that each section of pavement must be inspected every year or that 100 percent of the area of each section must be inspected.

If a windshield survey is used to inspect the pavements, then normally the entire management or data collection section is inspected each time. However, if a walking survey or an automated survey vehicle is used, the inspection costs can be reduced by inspecting only a portion of each management or data collection section. The management or data collection can be divided into sample units or inspection units of approximately equal size, and only a portion of those are inspected.

Frequency of Surveys: Not all sections need to be inspected every year, especially if the PMS has a method of projecting future condition. More important sections, such as those on the interstates, can be inspected every year while those sections with lower usage can be inspected every second or third year. Those in better condition and with lower rates of deterioration can be inspected less often than those deteriorating quickly.

A condition projection method can be used to bring all section conditions to a common period for analysis.

5.13 Summary

Finally, two appendices have been included. Appendix 5A is a sample of the distress evaluation charts used in New Mexico for their manual survey. Appendix 5B is a reproduction of the draft AASHTO protocols for pavement condition data collection. They have been included as information for users of this workbook.

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MODULE 6

PAVEMENT CONDITION INDICES

6.1 Module Objectives

This module describes the historic development of pavement condition indices, the different types of indices, and their basic functions in a PMS. The module will also describe in detail how they may be developed and how they are computed. Several case studies are presented as examples of the use of different indices in a PMS.

Upon completion of this module, participants will be able to:

- Describe the different types of pavement condition indices
- Describe how condition indices are used in a PMS
- Describe how a condition index is developed
- Determine if an index is satisfying its intended purpose

6.2 Historical Development of Pavement Distress Indices

Pavement distress information is usually converted into a condition index. The condition index combines information from all of the distress types, severities, and quantities into a single number. This number can be used at the network level to define the condition state, to identify when treatments are needed, for ranking or prioritization, and as the number used to forecast pavement condition. The condition index may represent a single distress such as fatigue cracking or a combination of many pavement distresses which is then usually referred to as a composite index. Additional information has also been included in some indices such as traffic levels, highway class, etc. to produce priority ranking indices.

One of the earliest pavement condition indices was the Present Serviceability Rating (PSR) developed at the AASHO Road Test. The PSR was developed at the AASHO Road Test by having raters riding in an automobile assign a pavement condition value that indicated the level of service the pavement provided. Researchers wanted, however, to measure this index objectively. Therefore, a relationship was developed between the mean PSR assigned by the panel, and some objective measurements such as roughness, rutting and cracking *(1)*. The new index, which was based on the values of pavement smoothness, rutting cracking and patching was called the Present Serviceability Index (PSI). The resulting relationship for PSI for flexible pavements is shown in Equation 6.1.

Notice the difference between the PSI and the PSR. The “Index” is a statistical estimate of the panel’s mean “Rating”.

Equation 6.1 allowed the calculation of PSR directly from objective measurements. At the time it was a tremendous advancement for pavement management because it provided a network health index that could be calculated from objectively measured condition data. This was a breakthrough because panel ratings were expensive and unstable. Collecting RD, SV, C and P measurements was also expensive, but it was far more reliable.

Equation 6.1

$$\mathbf{PSI = 5.03 - \log(1 + SV) - 1.38(RD)^2 - 0.01(C + P)^{1/2}}$$

Where

PSI =	the present serviceability index which is a statistical estimate of the mean of the present serviceability ratings given by the panel,
SV =	Slope variance over section from CHLOE profilometer (slope variance was an early roughness measurement)
RD =	mean rut depth (in.),
C =	cracking (ft / 1000 ft^2) (flexible),
P =	patching (ft^2 / 1000 ft^2).

The Federal Highway Administration (FHWA) still requires states to submit PSR data for nationwide road health monitoring. The FHWA guidelines for collecting the PSR data are shown in Table 6.1.

PSR ranges from 0 to 5 based on a description of rideability, physical distress, and rehabilitation needs *(2).*

The AASHO Present Serviceability Rating or the Present Serviceability Index was adopted by many states as their pavement distress index in the development of their PMS. These are the most recognized indices that were specifically developed to reflect the special quality or service (ride) a pavement provides to the user (vehicle passenger).

In the late 1960's more unique indices were developed by several states as they developed their own pavement condition surveys *(3).* These indices were often developed through consensus when considering which distress to include and how they were to be computed.

The U.S. Army Corps of Engineers developed a very complete condition index for a pavement management system in 1976 *(4).* This included pavement condition survey procedures and a detailed method for calculating a Pavement Condition Index (PCI), which is still used today by many agencies. The computational procedures for this index will be shown later in this module *(4).*

As pavement management systems evolved to more complex systems, the form and utility of the indices used changed as well. Composite indices provide a fairly good indication of the general condition of the highway system. They indicate when action is needed but may not be discerning enough to help identify what treatment should be considered. Thus, they limit the ability of a PMS to efficiently and practically compute life-cycle cost analysis and perform network optimization. More distress specific indices are used to provide more information for the analysis requirements in the more

Table 6.1 FHWA guidelines for collecting PSR data

Verbal	Description	PSR
Very Good	Only new, superior (or nearly new) pavements are likely to be smooth enough and distress free (sufficiently free of cracks and patches) to qualify for this category. Most pavements constructed or resurfaced during the data year would normally be rated very good.	5.0 4.0
Good	Pavements in this category, although not quite as smooth as those described above, give a first class ride and exhibit few, if any, visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalding.	3.9 3.0
Fair	The riding qualities of pavements in this category are noticeably inferior to those of new pavements, and may be barely tolerable for high speed traffic. Surface defects of flexible pavements may include rutting, map cracking and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and cracking, and some pumping.	2.9 2.0
Poor	Pavements in this category have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes raveling, cracking, rutting, and occurs over 50 percent, or more, of the surface. Rigid pavement distress includes joint spalling, faulting, patching, cracking, scaling, and may include pumping and faulting.	1.9 1.0
Very Poor	Pavements in this category are in an extremely deteriorated condition. The facility is passable only at reduced speeds, and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.	0.9 0.0

sophisticated PMS. The distress specific indices used by different states usually consist of at least cracking, rutting and ride, but they may also consider the various cracking categories. More information on the development and computation of individual distress indices as well as composite indices will be discussed in a later section.

In addition, a brief summary of current practices in various states will be included.

6.3 Need for Pavement Condition Indices

Condition indices are used in most pavement management systems for the following four basic reasons *(5):*

- Trigger treatments
- Calculate life-cycle costs
- Evaluate the network condition
- Make use of the same relative scale between systems

Trigger Treatments: During a PMS analysis, a list of maintenance and rehabilitation strategies is generated. In generating this list, it is important that only feasible treatments are considered; otherwise the list would be infinitely long. To make the list include only feasible treatments, the PMS needs to know when a treatment is feasible and when it is not.

The process used by most PMS can be described as a simple decision process, where decision trees or triggers are used. The major inputs to this process are the condition indices. For example, with a treatment such as a "thin overlay", a condition index is needed to indicate when a road is in a condition that makes applying a 'thin overlay' feasible.

Feasibility can be examined from two perspectives: (1) operationally, and (2) economically. It is important not to confuse them. From an operational point of view, a thin (25 mm) overlay is sometimes impossible to actually place on the pavement. Consider a road with ruts, distortions, and severe roughness. If a PMS included a thin overlay treatment on the list of strategies for that pavement section it would lose credibility.

Therefore, from an operational perspective, the PMS needs condition indices to indicate when a road is outside the operationally feasible zone of receiving a particular treatment. Usually agencies begin their PMS by mimicking current practices, and thus this usually defines what is feasible from the operational point of view.

Calculate Costs: Pavement condition indices are used to help calculate better cost estimates for the full range of pavement management strategies. This can assist in making better cost projections.

There are many ways condition indices can help calculate costs precisely. The cost of applying the same treatment changes with circumstance. For example, it costs more to fill cracks on a road with many cracks than on a road with few cracks. Or, it costs more to overlay a road with fatigue cracking than a road without fatigue cracking. Or, it costs more to fill potholes on a road with many potholes than on a road with few potholes. Then there is a leveling course for uneven surfaces, drainage repair for poor drains, base repairs for high deflections and so on.

Not only can condition indices signal the need for extra work, sometimes they can also be used to estimate quantities required for activities such as crack filling or patching.

EVALUATE NETWORK HEALTH: A PMS is a tool an agency uses to get information to help make decisions. The individual condition indices used for calculations within a PMS are one-dimensional i.e. they only describe one measure of condition. An example is a ride index or a fatigue cracking index.

Composite indices have been developed by many agencies and are used to describe or account for many different measures of condition at once. Composite indices are often a combination of all of the distress data collected by an agency. They are often calculated from ride, cracking, and rutting and condition data at a minimum. The relative weighting of each distress within the composite index is often based on the collective opinion of those within the agency as to which are the most important pavement distresses.

Composite indices are used by most agencies to show the present condition (health) of the pavements in their highway system. The use of composite indices allows the comparison of roads that are experiencing distinctly different distresses but are all considered deficient. The composite index is also easier to explain at the non-technical level within and outside of an agency.

COMPARING ROADS WITH DIFFERENT DISTRESSES: The fourth reason why condition indices are needed is to compare one road directly to another that may have experienced different deterioration patterns. As long as different distress indices such as fatigue cracking, rutting, and ride are developed with different units but with the same relative scale, different roadways with different distresses may be compared to each other. In some cases, agencies have developed unitless scales to minimize the differences between indices.

With these unitless indices, a value of forty may represent a bad condition for one index, and also represents the same level of bad condition for another. In other words, forty is forty, no matter which measure of condition it stands for. This requires careful calibration between indices.

In *Ref. (6)*, the authors provided more specific benefits that can be derived from the use of pavement distress indices. They emphasize that:

§ Any pavement distress index allows better communication between the highway engineers of a state. For example, if the rating scale of the distress indices is 0 to 100 (100 = perfect pavement) and the threshold value is 60, then a value of a distress index of a pavement section of 45 has the same specific meaning to all engineers, regardless of the geographical location.

§ Pavement distress indices also permit highway organizations to establish a standard critical threshold level below which the pavement is considered unacceptable and in need of major maintenance or rehabilitation. This critical value may vary with the functional classification of the pavement (i.e., Interstate versus farm to market). For each distress index or for all indices, it is also possible to establish various threshold levels whereby one level will indicate the need for routine maintenance, another the need for minor repairs, and another to identify major rehabilitation needs.

§ Pavement distress indices also permit highway organizations to rank roads and highways for their maintenance / rehabilitation activities.

- Some distress indices such as PSI relate subjective ratings to objective distress measurements.

- Pavement distress indices collected over several years allow the SHA to determine the rate of deterioration of the different pavement sections of the network and permit engineers of an agency to modify or calibrate their performance prediction mode is based on this information.

- The distress indices allow the pavement designer to look back at the design method and analyze the effects of various design attributes on the pavement distress.

- If each distress index is calculated based on only one distress type (itemized distress indices), then it is possible to determine the relative amount of damage attributed by each distress mechanism. Hence, it is possible to conduct more detailed analyses of feasible rehabilitation alternatives.

- The distress indices allow highway engineers to assess the state of “health” of the pavement network and its rate of deterioration. This information along with the proper analysis of the cause of pavement distress, repair techniques and their associated costs are used to estimate the network’s needs.

In short, pavement distress indices form the numeric basis for quantifying pavement distress and may be used in many forms and processes within a pavement management system.

6.4 Development and Calculation of Pavement Distress Indices

As discussed in Module 5, it is common for agencies to describe pavement distress in terms of its severity and its extent. Severity indicates how bad the distress is. Extent indicates the quantity of distress. Extent can be estimated for an entire section length, estimated over a representative area (such as 100 m per km) or measured. Together, these two parameters can describe a great deal about a particular distress. In North America, this has become the standard manner to collect data for individual distresses.

Consider the example of a pavement distress matrix similar to the one shown in Table 6.2. The rows of the matrix divide the severity into three categories: low, medium and high. The columns represent five categories of extent. During a condition survey a rater describes the condition of the road by placing a check mark in one or more cells.

Table 6.2 **Example Matrix for Collection of Distress Extent and Severity**

	Extent				
Severity	None	1-10%	10-25%	25-50%	>50%
Low					
Medium			✔		
High					

Some survey procedures require the rater to put one check mark for each severity (i.e., one per row). Others simplify this by requiring the rater to only put one check mark in the cell representing the most predominant condition. Table 6.2 illustrates the case where the most predominant distress is recorded. In this example, the rater checked the cell for Medium Severity with an extent between 10 to 25%.

To transform this data into a meaningful condition index, deduct values are needed. Deduct values are points which are used to compute the index based on the severity and extent of the distress represented. The development and calibration of the proper deduct value is the most complicated and critical part in the development of a pavement condition index.

The concept of deduct values is described by its name. The index based is calculated by deducting a number of points from the index value of a pavement in perfect condition, depending on the severity and extent of the deficiency. The value deducted also depends on the condition of the pavement. The number of points deducted is called the deduct value. The very simple formula which uses a deduct value to compute a distress index is shown in the following equation.

Equation 6.2

$$PCI_i = PCI_{max} - \Sigma \text{ Deduct}$$

Where

PCI_i = individual condition index based on measured condition 1

PCI_{max} = value for perfect condition with no measured defects

Deduct = deduct value assigned to distress type, severity & extent

Obviously, using this equation implies that the condition index gets worse as the deduct value increases. Assume an agency uses an index with a scale from 0 (bad) to 100 (perfect = $D_{max,i}$). If the pavement was in perfect condition, the deduct value would be 0, resulting in an index value of 100. If the pavement was in terrible condition, the deduct value would be 100, resulting in an index value of 0.

The relative value of the pavement distress index which represents the condition of the pavement and the shape of the resulting pavement deterioration depends entirely upon the development of the deduct values. Two basic approaches are often used to develop deduct value:

- Expert opinion
- Engineering or mathematical

Both approaches have many variations.

The easiest way to allocate deduct values is to use expert opinion. Most agencies that have developed pavement condition indices begin with this process. To use this approach, agency experts meet to assign deduct values to each cell in a matrix similar to the one in Table 6.2. This approach, however, has provided for some awkward looking pavement trends, or in some cases has not produced any reasonable trends at all. If not approached properly, expert opinion can give erratic results at best or simply incorrect results at worst *(5,7)*.

To illustrate this process, consider the following example of historic deterioration trends for a typical road. In this example, Table 6.3 shows where a rater has placed his or her check mark during eight consecutive condition surveys. These eight surveys were conducted every two years, for a total of sixteen years. Together, then, the eight check marks indicate how the condition of the road changed during the sixteen years.

Table 6.3 Example of a typical failure trend for eight surveys over 16 years.

Severity	Extent				
	None	1-10%	10-25%	25-50%	>50%
Low	✔ $_2$	✔ $_4$	✔ $_6$ ✔ $_8$		
Medium			✔ $_{10}$	✔ $_{12}$✔ $_{14}$	
High				✔ $_{16}$	

This example provides an illustration of the historic condition trends for one arbitrarily selected road segment. The age of the road is indicated with a subscript on each check mark. Notice that the road had no distress when it was two years old. This check mark was from the first survey. The next survey at age four, resulted in a check mark in the 1-10% extent, low severity cell. In the eighth and final survey, when the road was sixteen years old, the check mark was placed in the 25 to 50% extent, high severity cell.

Double check marks in two of the cells do not imply that there was no change in pavement condition, but that change stayed within the limits of that cell. For example between the 12th and 14th years the distress may simply have progressed from 30% to 45%. The fact that the deduct values did not change is one of the primary problems in using a deficiency matrix or blocks of extent rather than measured values of extent. On the positive side, this approach is much simpler to survey and use and has been found accurate enough for network level PMS processes *(7)*.

In a sense, Table 6.3 shows the 'failure mechanism' of this road. By following the path the check marks took through the matrix, an agency can see how the condition in the field changed over time. The next step now is to see how the distress index for that road changed over time. To do this we need deduct values for each of the cells with check marks. Table 6.4 illustrates this concept. This type of matrix must be developed for each of the distress types included in the survey.

Table 6.4 Example deduct values assigned by expert opinion.

Severity	Extent				
	None	1-10%	10-25%	25-50%	>50 %
Low	0 $_{2}$	20 $_{4}$	30 $_{6,8}$	40	50
Medium	0	35	40 $_{10}$	60 $_{12,14}$	75
High	0	50	60	80 $_{16}$	100

The age is again used as a subscript to show the path the check marks took through this matrix. The subscripts on the deduct values help illustrate the road's failure mechanism. Another road may take an entirely different path through the matrix as it deteriorates over time. Failing to realize this leads to one of the biggest problems in assigning deduct values. If the deduct values are not smooth for each possible path, the performance curve for any road following that path will also not be smooth.

Plotting the condition index versus age for the example road gives the curve shown in Figure 6.1. The shape of this curve is totally dependent on the deduct values assigned in Table 6.3, and the path through the distress matrix. Any time one of the deduct values changes, a point on the curve will also move. That would change the shape of the curve. Two roads could take two entirely different paths through the matrix. This too would change the shape of the performance curve.

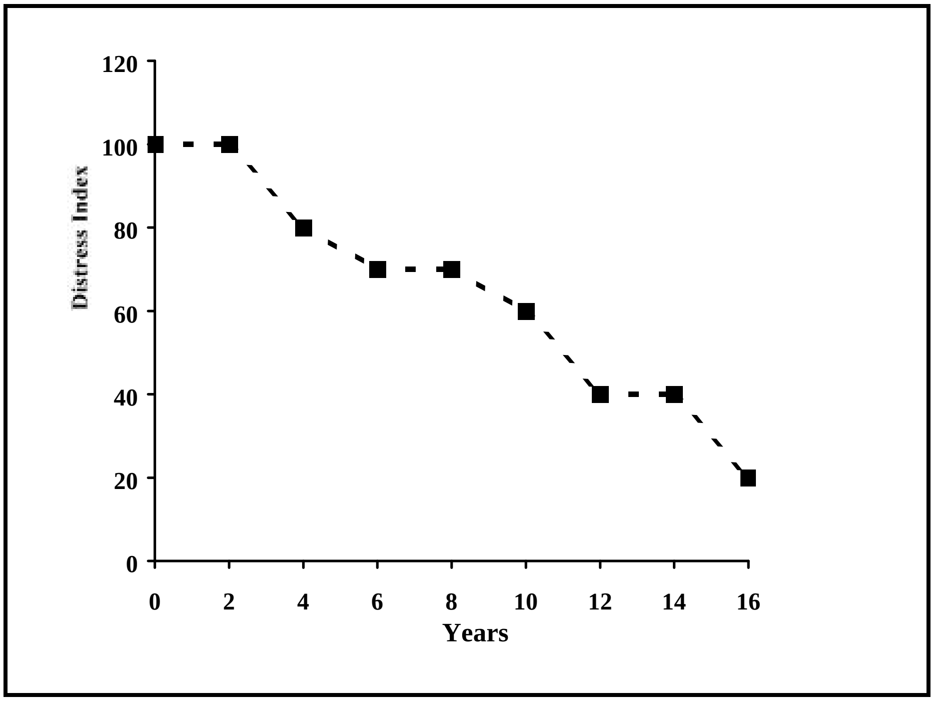
In order to develop smooth and continuous performance curves, it is important that deduct values be carefully assigned. The following discussion gives three examples of a more scientific approach developed to help automate the process. These approaches help express deducts as a function of extent and severity so it is easier to control the final shape of the performance curves.

One of the best introductions to developing individual condition indices is included in *Ref. (6)*. The following section is paraphrased from this reference. The authors introduce three terms that are essential for developing individual condition indices:

Index Scale: The index scale is the scale used for the condition index. There are an infinite number of index scales to choose from. Some, such as the scale for the International Roughness Index (IRI), are open ended or 'unbounded', and can theoretically go to infinity. Others are bound by maximum and minimum values such as 0 (bad) to 100 (good), 0 (bad) to 5 (good), or 100 (bad) to 0 (good), to name a few.

The first step in developing individual indices will be to decide on a scale. A scale of 0 (bad) to 100 (good) is used as an example. Note that the minimum and maximum are only examples, and the fact that the scale decreases with decreasing condition is also only an example. This is not the only way of developing an index. In order to be able to compare one distress index with another, it is important that the same scale be used for each index.

Figure 6.2 Plot of example distress values versus age for deducts assigned by expert opinion.



Threshold Value: The threshold represents the value below which a pavement is considered to be in unacceptable condition based on whatever scale is being used. On a scale of 0 (bad) to 100 (good), a value of 60 is a reasonable example of a threshold value. This rating is based on the assumption that 40 deduct points were subtracted from the maximum rating of 100. One of the challenges involved in developing condition indices and assigning deduct points is ensuring that the index only falls below the threshold value when the road truly is in unacceptable condition, and not before. In many instances, threshold values are set consistently for each of the distress indices so that unacceptable conditions are reported consistently.

Engineering Criteria: These values relate the actual condition of the road to the threshold value. The engineering criteria are established setting the amount of distress for each severity level at which the road reaches an unacceptable condition.

For example, assume that three severity levels; low, medium and high, exist for a particular distress index. In this instance, three criteria would have to be defined. These three engineering criteria are established at the extent at which each of the three severities reaches the threshold value. In other words, the engineering criteria represent the values at which the threshold values would be reached if only that distress at that particular severity level were present. To illustrate how these values are used in this example, assume engineering criteria of 70% for low severity, 20% for medium severity, and 10% for high severity are used.

Ref. (5) provides examples of how the engineering criteria used. To demonstrate these examples, a sample graph of deduct values versus extent are shown in Figure 6.2. The three lines on this graph are determined by first calculating the deduct value of 40 from the threshold value of 60 (i.e. 100 – 60 = 40). Next, the threshold line is drawn horizontally at the deduct value of 40. The next step involves extending the engineering criteria from the axis up to this horizontal threshold line. Finally, a line joining each of the three intersecting points to the origin is drawn. These lines represents the deduct curve for the respective severity levels.

To use this graph, enter on the x-axis an extent, go up to the respective severity line, and then across to get the deduct value. Alternatively, the formula for each line can be derived so that the deduct value can be directly calculated. Since the slope of each curve equals the threshold deduct value (40) divided by the respective engineering criteria (70, 20, 10) as shown in the following equation:

Equation 6.3

$$DV_s = (D_{max} - TV_s)/Ec_s \times EXT_s$$

Where:

DV_s	= current deduct value for severity *s*
D_{max}	= maximum value on index scale
TV_s	= threshold value for severity *s*
EC_s	= engineering criterion for severity *s*
EXT_s	= current extent for severity *s*

Table 6.5 shows a matrix of the deduct values that result from using Equation 6.3 for each severity level in the example. To obtain these deduct values, assume the extent for each severity is at the midpoint in the range. Using the midpoint, the deduct value can be determined for each severity level. For example, assume an extent of 5% was used for the 1-10% range, and 17.5%, 37.5% and 75% for the other three ranges, respectively.

The deduct values can then be determined from Figure 6.2 and the results entered into Table 6.5. Note that when the deduct value is determined to be greater than 100, a ‘n/a’ was placed in the cell. This was done to prevent a negative condition index value since deducts cannot be more than 100.

Figure 6.2 Deduct values for example using the straight line approach *(5,8)*

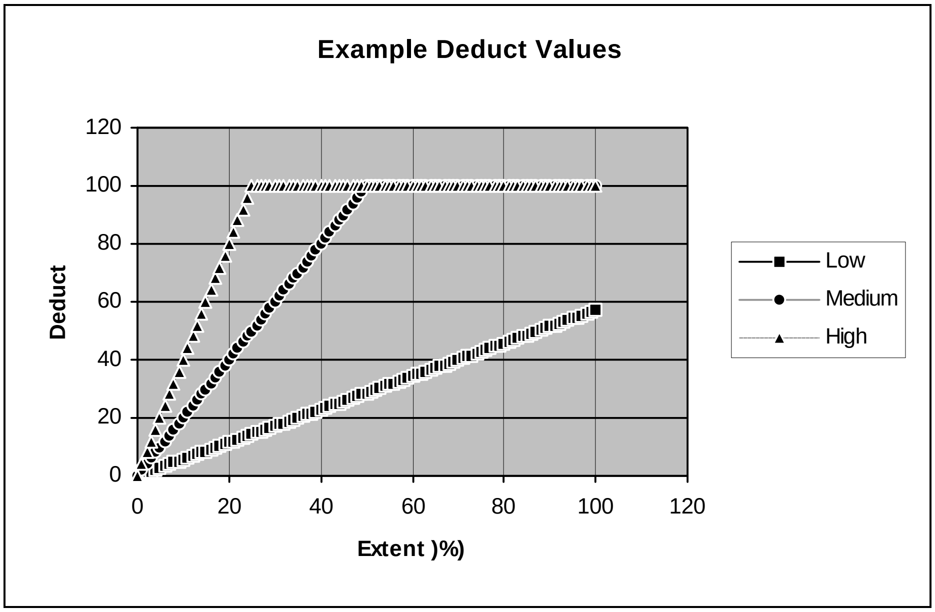
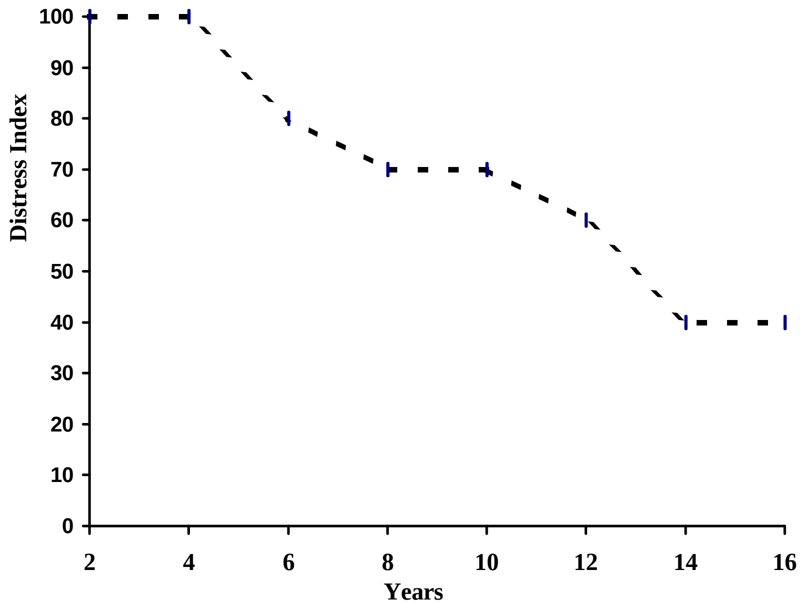


Table 6.5 Example deduct values assigned by the straight line approach *(5,8)*

Severity	Extent				
	None	1-10%	10-25%	25-50%	>50%
Low	0 *2*	3 *4*	10 *6,8*	21	43
Medium	0	10	35 *10*	75 *12,14*	n/a
High	0	20	70	n/a *16*	n/a

Recall the plot resulting from the deduct values assigned by the experts in Figure 6.1, and the upward trend between years 12-14. Figure 6.3 shows the performance curve that results from following the same path through the matrix using the new deduct values calculated in Table 6.5. This time there is an improvement between years 12 and 14.

Figure 6.3 Example distress values versus age for deducts assigned by the straight line method



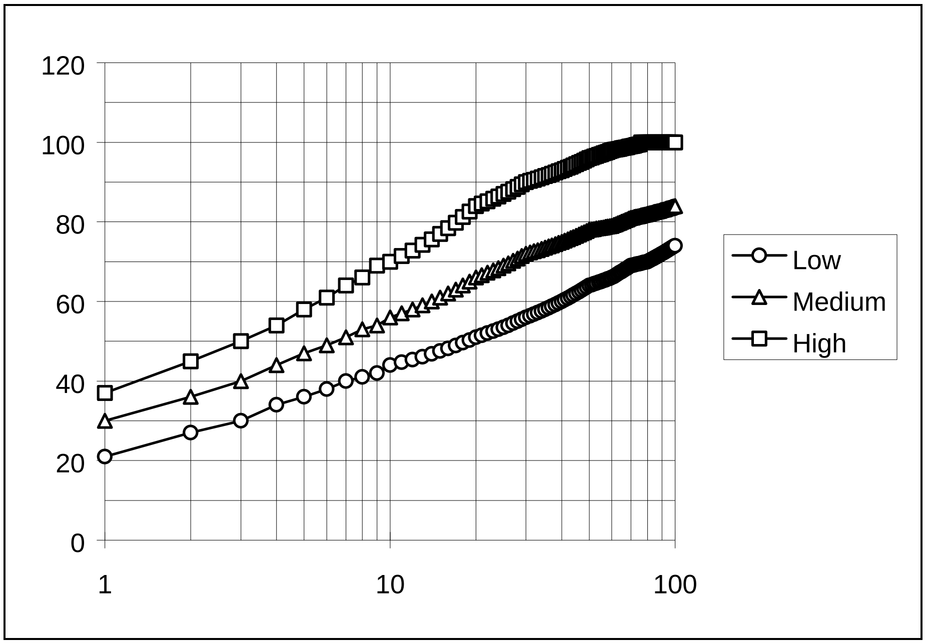
The issue that ultimately has to be addressed in developing the deduct values is the shape of the performance curves. In order to address this issue, an agency must be able to define the most likely path a typical road will take through the severity/extent matrix as the road deteriorates. In turn, this is also affected by the values chosen for the severity and extent.

ASTM Standard D5340 provides a set of deduct value versus extent curves based on work done by *Ref. (4).* These curves are different from those discussed earlier as a curved line on a semi-log graph was used as opposed to a straight line on a normal graph. Figure 6.4 illustrates the curves given for alligator (fatigue) cracking. The x-axis represents the density or extent, while the y-axis represents the deduct values.

Since this graph was taken directly from the reference, it is not expected to have the same threshold value of 60 as in the example above. If this index did have the same threshold value, then the engineering criteria would be 1.5% for high severity, 3% for medium severity and 8% for low severity. To confirm this, follow the line from the deduct value of 40 across the graph until it intersects each of the lines.

Conversely, if this index did have the same engineering criteria as our example (70, 20, 10), then the threshold value would be somewhere around 35 (with a deduct of 65). Once again, to confirm this follow the line from the deduct value of 65 across the graph until it intersects with the three lines.

Figure 6.4 Deduct values for fatigue cracking based on ASTM D5340 *(4,5)*



The resulting matrix of these deducts is shown in Table 6.6. Once again, the midpoint of the extent range was used to arrive at these values. Note that the subscripts indicate the age of the example road when the surveys were performed.

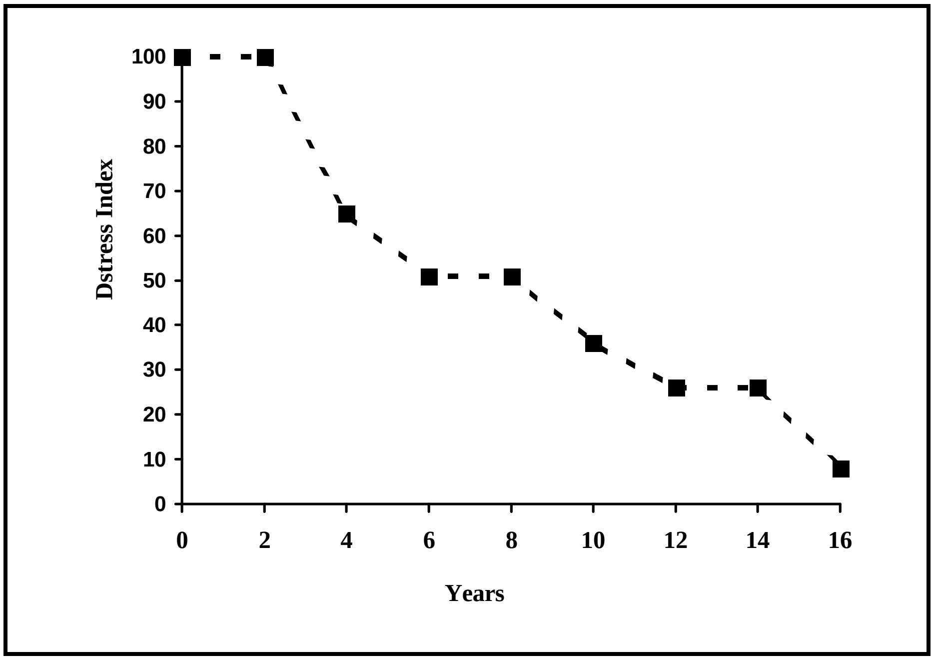
Table 6.6 Example deduct values assigned by a semi-log approach for fatigue cracking, from ASTM D5340 *(4,5)*

Severity	Extent				
	None	1-10%	10-25%	25-50%	>50%
Low	0_{2}	35_{4}	$49_{6,8}$	58	70
Medium	0	45	64_{10}	$74_{12,14}$	82
High	0	56	81	92_{16}	99

Notice the fairly large deducts for the first range (1-10%). This indicates that alligator or fatigue cracking has a large impact on deterioration at its early stages. This pattern affects the shape of the resulting deterioration curve. In this example, the deterioration curve for alligator cracking would reflect more of an S-shaped curve rather than the concave curves that may be more traditional.

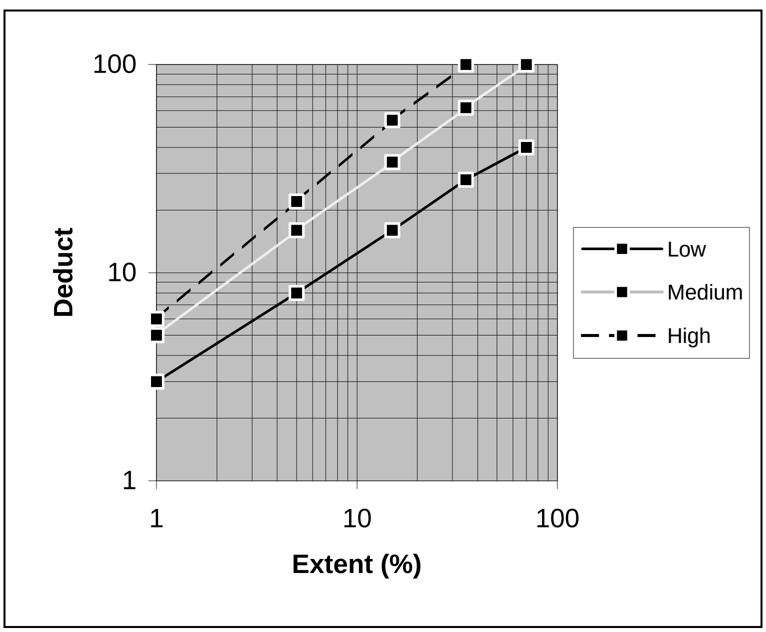
Figure 6.5 shows the performance curve which results from following the same path through the matrix using the new deduct values. This time there is an improvement between years 6 and 8. The important thing to notice regarding this curve is the fact that it is concave upwards. This happens because of the huge initial deduct values.

Figure 6.5 Example distress values versus age for deducts assigned by semi-log approach *(4,5)*



A variation of the straight line approach described in *Ref. (6)* was used in the development of pavement distress indices in South Dakota *(7)*. These curves were different from both previous examples because a straight line on a log-log graph was used. Figure 6.6 illustrates the curves developed for alligator (fatigue) cracking in South Dakota.

Figure 6.6 Deduct values for example using log-log approach.



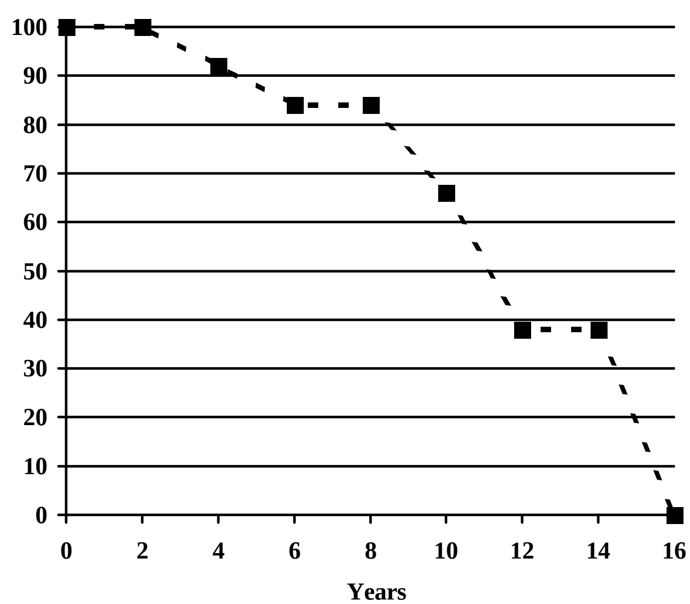
The resulting matrix of these deducts is shown in Table 6.7. Once again, the midpoint of the extent range was used to get these deduct values. As before, the subscripts indicate the age at which the surveys were performed. This time the deduct values did not take a huge jump in the initial extent category. This, as can be seen later, results in a concave downward slope.

Table 6.7 Example deduct values assigned by log-log approach

Severity	Extent				
	None	1-10%	10-25%	25-50%	>50%
Low	0_{2}	8_{4}	$16_{6,8}$	28	40
Medium	0	16	34_{10}	$62_{12,14}$	100
High	0	22	54	100_{16}	n/a

Figure 6.7 shows the performance curve which results from following the same path through the matrix using the new deduct values in Table 6.7. This time there is an improvement between years 12 and 14. The important thing to notice regarding this curve is the fact that it is concave downwards. This is the shape that is more traditional.

Figure 6.7 Example distress values versus age for deducts assigned by log-log approach.



Whatever method is chosen to assign deduct values for the individual condition indices is up to each agency. Each method has its strengths and weaknesses, and, each method can produce a different shape in the performance curve. After deciding on the threshold values and engineering criteria, an agency should then focus on:

- What is the most likely path through the matrix for that condition on a typical road?
- What should the shape of the performance curve be for that condition based on that path?

BASIC CRITERIA: As a final comment in developing condition indices, the following two very basic criteria should be considered *(8):*

The first and most critical criterion is that the deduct values should be scaled such that the resulting condition index threshold value (or action point) occurs at about the middle of the scale *(5)*. In the past, some have established the "should consider action" level at about 60 % of the scale and the "must consider action" level at 40% of the scale.

This concept is similar to the common Pavement Serviceability Index (PSI) developed by AASHO in the early 1960s following the AASHO Road Test. Recall that the PSI is a 0 to 5 scale where a value of 3 is usually considered the proper timing to take action on a high quality roadway, and a value of 2 is considered fairly poor condition for even a secondary road. The value of extent and severity corresponding to the threshold value is sometimes referred to as the engineering criteria *(5)*.

The second criterion is that the transition of the deduct values through the various levels of the distress matrix should produce a condition index that transitions as smoothly as possible with time. Pavement distress is usually observed in the field as a continuous process with time, as the distress progresses through the full range of severity and extent. The trends of the pavement condition index in the PMS should correspond to the trends observed in the specific pavement section represented by that index. Most deficiencies, once they become apparent, tend to increase in both severity and extent at an increasing rate with time. Thus the pavement condition index, which is the numeric representation of the pavement condition in the field, should have the same trends with time as the deficiency appears to have in the field.

In general, those pavements that deteriorate rapidly after the last treatment tend to have a fairly linear form i.e. the rate of change in pavement condition is about the same from one year to the next. Those pavements that last longer before some distress is observed tend to be more exponential in form.

Pavements that have lasted an unusually long time before distress occurs tend to deteriorate quite rapidly in the end; thus they appear to have a very sharp exponential trend. Though this second criterion is not absolutely required for a PMS to function, it is necessary for the PMS to have wide acceptance and is the best utilization of the tool in the decision making process.

6.5 Current Practices in Determining Pavement Condition

In 1994, a survey of all the states was performed to summarize the current practices used to determine the condition of pavements in North America *(9)*. Nearly all the respondents (50 states and 9 Canadian provinces) indicated that the agencies are performing data collection activities in one or more of the four main areas of pavement condition evaluation. These four areas were described in more detail in Module 6, but to briefly recapitulate, are:

- Distress
- Roughness
- Structural
- Friction

The methods and procedures used for the collection of roughness data and friction testing are the most standardized practices being followed. Both the use of the South Dakota type profiling device and reporting of roughness in terms of the IRI has increased sharply.

Many of the agencies evaluate structural capacity, but practices vary widely in programming, conducting, and reporting procedures. This information is used primarily for project-level design rather than at the network-level.

Nearly all the agencies perform friction or skid testing and ASTM methods are most commonly used. Only a few agencies perform friction testing on a continuous, annual, network-survey basis.

The widest variation of practices occurs in the collection and use of pavement distress information. Many of the agencies have recently updated their procedure manuals. Field survey procedures and distress definitions vary greatly. The methods and condition indices used allow little opportunity for exchange of performance data among agencies.

Approximately 80 percent of the agencies use a distress index, serviceability index/rating, or a priority rating as the output for the distress survey. There does not appear to be any evident trends in the way these indices have developed, although formulae are used more frequently than other methods. Over two-thirds of the agencies combine their distress index or ratings with other indices or ratings. The most often used additional index is roughness.

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MODULE 7

ESAL FLOW MAPS

7.1 Module Objectives

The basic concepts of characterizing truck loading by the use of Equivalent Single Axle Loads (ESALs), and how they are determined, are discussed in this module. The application of ESALs rather than basic traffic volumes in a PMS is discussed as well as the calculation of accurate ESAL estimates considering daily, monthly, and seasonal truck flows for use in pavement mangement systems and in pavement design.

Upon completion of this module, the participants will be able to:

- Describe what ESALs are and why they are used in pavement design and in PMS.
- Describe how ESALs are determined and what measurements are needed to develop an ESAL flow map.
- Describe the basic equipment needed, and what sampling plan may be required to collect sufficient truck volumes and classifications to develop reasonably accurate ESAL estimates for PMS and pavement design needs.
- Understand the benefits of having more complete ESAL estimates in a PMS and how they can be used to improve the analysis and project selection.

7.2 Introduction

This module provides information on the collection and evaluation of traffic loading data for pavement design and pavement management needs. Truck traffic loading evaluation should be performed as part of the overall engineering evaluation of a particular project for pavement design purposes. For the very same reasons, a general traffic file containing truck traffic loadings for each highway should be part of a pavement management system. As an example, future traffic levels may dictate whether patching or sealing may be an adequate treatment or if an overlay is required. If an overlay is required, the magnitude of that future traffic loading will determine in large part what the thickness of the overlay will be.

A complete traffic evaluation provides information on the estimation of past and current loadings, on the structural adequacy of the existing pavement, and on the expected future traffic loadings. By knowing the past and current traffic loadings, comparisons can be made with the design traffic to provide an indication of how well the pavement is performing and if a structural deficiency exists. The consideration of the future traffic loadings can be an important part of rehabilitation planning and programming and may also influence the ultimate selection of the rehabilitation strategy.

An evaluation of traffic loadings is one of the most important factors in any aspect of pavement design and rehabilitation and consequently it is of equal importance for pavement management. The collection of representative traffic data and its proper interpretation and analysis is critical in achieving adequate designs.

One problem in evaluating traffic loadings is that a variety of vehicles utilize a roadway, each having different gross weights, axle types and weights, and axle configurations. It is very difficult to interpret data that consist of a wide array of axle loads and types and apply them directly in a pavement design and evaluation. It is much more convenient to employ a standard measurement of traffic loading in which all axle loads applied to a pavement structure by the mix of vehicle types are converted into an equivalent number of loadings of a standard axle. Most highway agencies use a standard axle and the one employed in most design methods is the 18-kip (80 kN) equivalent single-axle load (ESAL).

7.3 Load Equivalency and Truck Factors

Load equivalency factors (LEF) and truck factors (TF) play an integral part in the development of the number of 18-kip (80 kN) ESAL applications for rehabilitation design. However, these two factors are often confused and it is important that the distinction between the two be understood.

Load Equivalency Factors: Each vehicle traversing a pavement produces deflections, stresses, and strains in the pavement/subgrade layers. Each response inflicts an infinitesimal amount of damage to the pavement. With repeated applications, the amount of damage accumulates and reduces the remaining service life of the pavement. Different vehicle types, load magnitudes, and axle load configurations all produce different pavement responses that result in different levels of damage to the pavement.

Since it is very difficult to assess the damage caused by every vehicle type that may utilize a pavement, design engineers find it useful to express the amount of damage caused by each vehicle type in terms of the equivalent amount of damage caused by a standard axle. As was mentioned earlier, the standard axle used by most highway agencies and design procedures is the 18-kip (80 kN) single axle. The basis for the conversion of the mixed traffic loads to the equivalent number of standard axle load applications was developed from data collected at the AASHO Road Test, conducted in Ottawa, Illinois from 1958 to 1960 (*1*). At the Road Test, similar pavement designs were loaded with different axle types and loadings so that the direct effect of each axle type and load on pavement damage (expressed in terms of present serviceability loss) could be ascertained. A load equivalency factor was defined as follows:

Equation 7.1: Calculation of load equivalency factor

$$\text{LEF} = \frac{\text{Number of 18 kip ESAL to cause loss of serviceability}}{\text{Number of X kip axle loads to cause same loss}}$$

Where

X = Axle load for which equivalency is calculated.

For example, consider two identical pavement structures that are subjected to loadings from two different axle types. Assume that the first pavement structure sustains 100,000 applications of an 18-kip (80 kN) single axle for a serviceability drop from 4.2 to 2.5, while the second pavement structure sustains 14,347 applications of a 30-kip

(133 kN) single axle for the same serviceability loss. The load equivalency factor for the 30-kip (133 kN) single-axle load is then:

$LEF_{\text{30-kip single}} = 100,000 / 14,347 = 6.97$

Or, 14,347 passes of the 30-kip (133 kN) single axle produce as much damage as 100,000 applications of the 18-kip (80 kN) single axle. In other words, 1 pass of the 30-kip (133 kN) single axle causes the same amount of damage as approximately 7 passes of the 18-kip (80 kN) single axle.

Empirical regression equations were developed from the AASHO Road Test data that express the relative amount of damage caused by each axle load and type in terms of the equivalent amount of damage done by an 18-kip (80 kN) single-axle load. Load equivalency factors for a terminal serviceability of 2.5 are illustrated in Table 7.1 (for flexible pavements) (*2*).

As an example in the use of the load equivalency tables, consider a flexible pavement with a structural number of 5.0 and a terminal serviceability ($P_{t)}$ of 2.5. Referring to Table 7.1 the following equivalency factors are obtained for the specified axle loads and types as shown in Table 7.2.

From Table 7.2, observe that one pass of a 30-kip (133 kN) single axle produces the same amount of damage as 6.97 passes of an 18-kip (80 kN) single axle. Additionally, one pass of a 48-kip (213 kN) tandem axle produces as much damage as 4.17 passes of an 18-kip (80 kN) single axle, and so on. The LEFs will change with structural number and terminal serviceability.

Note that a single axle is defined as an axle on a vehicle that is separated from any previous or succeeding axle by more than 96 in (2438 mm). A tandem axle is defined as two consecutive axles that are more than 40 in (1016 mm) but less than 96 in (2438 mm) apart. A tridem axle is three consecutive axles that are more than 40 (1016 mm) but not more than 96 in (2438 mm) from one of the other axles in the group (*1*).

The traditional relationship between pavement damage and the applied load is that damage increases to the fourth power as the axle load increases. For example, in the above table where the load is doubled (15-kip [67 kN] single axle to 30-kip [133 kN] single axle and 18-kip [80 kN] tandem axle to 36-kip [160 kN] tandem axle), the LEF increases approximately by a factor of 2^4, or 16. This concept is illustrated in Figure 7.1, which shows the increase in the damage factor (LEF) as the gross axle load is increased. Similar curves can be generated for tandem axles. Note that the benefits of distributing a load over a tandem axle are also apparent, as for the same gross weight the damage factors are much less for the tandem axle than for the single axle.

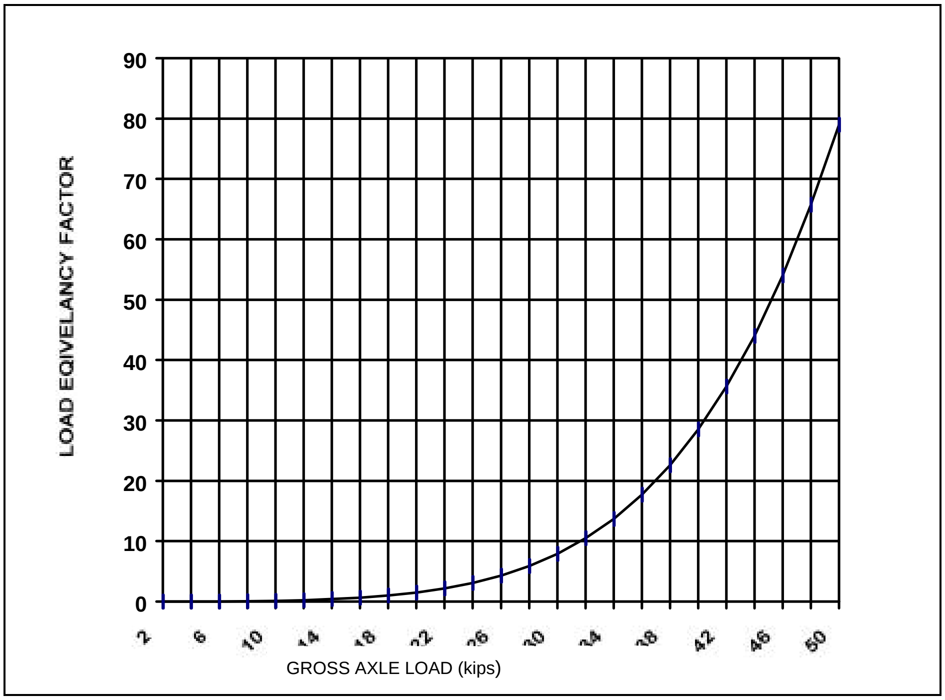
Table 7.1 Excerpt from AASHTO load equivalency factors for flexible pavements (*2*).

Axle load equivalency factors for flexible pavements, single axles and p_t of 2.5						
Axle Load (kips)	**Pavement Structural Number**					
	1	**2**	**3**	**4**	**5**	**6**
2	.0004	.0004	.0003	.0002	.0002	.0002
4	.003	.004	.004	.003	.002	.002
6	.011	.017	.017	.013	.010	.009
8	.032	.047	.051	.041	.034	.031
10	.078	.102	.118	.102	.088	.080
12	.168	.198	.229	.213	.189	.176
14	.328	.358	.399	.388	.360	.342
16	.591	.613	.646	.645	.623	.606
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.3	9.5	7.9	6.8	7.0	7.8
32	13.9	12.8	10.5	8.8	8.9	10.0
34	18.4	16.9	13.7	11.3	11.2	12.5
36	24.0	22.0	17.7	14.4	13.9	15.5
38	30.9	28.3	22.6	18.1	17.2	19.0
40	39.3	35.9	28.5	22.5	21.1	23.0
42	49.3	45.0	35.6	27.8	25.6	27.7
44	61.3	55.9	44.0	34.0	31.0	33.1
46	75.5	68.8	54.0	41.4	37.2	39.3

Table 7.2 Example load equivalency factors for various single axle types.

Axle Load and Type	**LEF**
15-kip (67 kN) single axle	0.49
18-kip (80 kN) single axle	1.00
30-kip (133 kN) single axle	6.97
18-kip (80 kN) tandem axle	0.08
36-kip (160 kN) tandem axle	1.38
48-kip (213 kN) tandem axle	4.17

Figure 7.1 **Relationship between damage factor (LEF) and gross axle load (*3*).**



Truck Factors: While the LEFs provide a means of expressing equivalent levels of damage between axles, it is more convenient to express that damage in terms of the average amount of damage inflicted by a particular vehicle. That is, the average damage done by each axle on a vehicle are added together and expressed as the total amount of damage done by the passing of that one vehicle. This addition is incorporated within the concept of the truck factor (TF), which is defined as the number of 18-kip (80 kN) ESAL applications per truck (or vehicle). A truck factor may be computed for each general truck classification or for all commercial trucks as an average for a given traffic stream. It is more accurate to compute truck factors for each general truck classification.

Typical truck factors for flexible pavements are given in Table 7.2 (*4*). This table provides truck factors for various truck classifications and also for different highway classifications. For example, a truck factor of 1.09 for "tractor semi-trailers 5-axle or more" means that 100 passes of this truck causes the same amount of damage as 109 passes of an 18-kip (80 kN) single-axle load.

Table 7.2 Distribution of truck factors for different classes of highways and vehicles (*4*).

Truck Factors						
Vehicle Type	**Interstate**	**Principal**	**Minor Arterial**	**Major Collector**	**Minor Collector**	**Range of TFs**
SU Trucks						
2-axle, 4 -tire	0.003	0.003	0.003	0.017	0.003	0.01 - 0.02
2-axle, 6-tire	0.21	0.25	0.28	0.41	0.19	0.19 - 0.41
3-axle or more	0.61	0.86	1.06	1.26	0.45	0.45 - 1.26
All Single Units	0.06	0.08	0.08	0.12	0.03	0.03 - 0.12
Tractor Semi-Trailors						
4-axle or less	0.62	0.92	0.62	0.37	0.91	0.37 - 0.97
5-axle	1.09	1.25	1.05	1.67	1.11	1.05 - 1.67
6-axle or more	1.23	1.54	1.04	2.21	1.35	1.04 - 2.21
All Multiple Units	1.04	1.21	0.97	1.05	1.08	0.97 - 1.52
All Trucks (including pu and panels)	0.52	0.38	0.21	0.30	0.12	0.12 - 0.52

The values given in Table 7.2 are averages from 1985 that are not representative of today's heavier trucks.

For many years, truck factors have been increasing for all categories of trucks. Reasons for this include the increase in the legal weight limit in the early 1980's, changes in axle configurations, and increased utilization of trucks. That is, a larger number of trucks are running full on both legs of their journeys, so that the number of "empty runs" has been reduced. It appears that the truck factor will continue to increase, a trend that must be considered in projecting future traffic loadings.

The observation of historical increases in the truck factor is illustrated in the following change in the average truck factor (all trucks except panels and pickups) for rural Interstate flexible pavements from 1971 to 1985:

Year	TF (ESAL/truck)
1971	0.595
1975	0.691
1979	0.766
1982	0.929
1985	0.992

The data from recently installed WIM equipment is believed to be more representative of the actual traffic loading, primarily because overloaded vehicles may bypass routes with weigh stations. A recent pavement performance study supports this assertion (*5*). In that study, mean truck values from seven WIM sites (Interstate highways) in four states gave an average TF that was 45 percent greater than the TF obtained from W-4 tables for 1987. Similarly, five WIM sites (off-Interstate highways) in five states gave an average TF that was 20 percent greater than the TF determined from the W-4 tables.

EXAMPLE APPLICATION OF LEF AND TF: In order to obtain a TF that can be used for 4R design projects, LEFs must first be determined. To do this, the LEFs are used to reduce a stream of different axle loads into an equivalent number of 18-kip (80 kN) ESAL applications. Then, the average TF can be computed by dividing the number of 18-kip (80 kN) ESAL applications by the number of trucks weighed. For example, consider the following information collected from 331 trucks weighed over a specific pavement section:

Axle Type	**Weight (Pounds)**	**Number of Axles**	**LEF**	**Number of 80 kN ESALs**
Single	18,000	100	1.00	100
Single	22,000	100	2.18	218
Tandem	18,000	1,000	0.08	80
Tandem	48,000	10	4.17	42
18-kip (80 kN) ESALs for all trucks weighed				440
Total number of trucks weighed				331
Truck Factor (= 440/331)				1.33

Thus, a total of 440 18-kip (80 kN) ESAL applications have been applied to the pavement, and since there were 331 trucks, this results in an average truck factor of 1.33 ESALs per truck.

7.4 Conversion of Mixed Traffic to ESAL Applications

The conversion of mixed traffic into the number of ESAL applications for rehabilitation design applies the concepts discussed in the preceding section. This calculation can be done to estimate the past traffic that a pavement has sustained (backcasting), or to estimate the future traffic loads that the pavement is expected to carry (forecasting). However, additional information is needed in order to perform the computation. The basic equation for the computation of the number of ESAL applications for one year is shown below:

Equation 7.2 Annual Equivalent Single Axle Loads for a given highway (*6*).

$$\mathbf{ESAL_{ANNUAL} = ADT \times TKS \times DD \times LD \times TF \times 365}$$

Where

ESAL	= Number of 18-kip (80 kN) ESAL applications in design lane for 1yr.
ADT	= Initial two-way average daily traffic, vehicles per day.
TKS	= Percent of ADT that is heavy trucks (FHWA class 5 or greater).
DD	= Directional distribution of truck traffic (decimal, not percent).
DL	= Lane distribution of trucks in design lane (decimal, not percent).
TF	= Lane distribution of trucks in design lane (decimal, not percent).

Equation 7.2 provides the number of ESAL applications for 1 year in a given lane. To obtain ESAL estimates over some design period, the computation must be done for each year with any appropriate growth rates (say, on truck volumes or on the truck factor) applied over that design period. The ESALs from each year are then added up to determine the cumulative ESAL estimate. This section describes the various elements needed for that ESAL computation. It should be recognized that the ESALs calculated represent the loads applied to a single pavement lane, often referred to as the design lane. Thus the total ESAL calculation must reflect directional and lane distributions.

TRAFFIC VOLUME AND GROWTH: Most highway agencies collect vehicle volume and classification data on a regular basis at many locations throughout their highway network. This data forms the foundation for estimating past and future traffic loadings. As a minimum, average daily traffic (ADT) and average daily truck traffic (ADTT) should be obtained. The ADT is generally recorded as the two-way (both direction) traffic count.

TRUCK VOLUME GROWTH RATES: In order to obtain a reasonable estimate of future traffic loadings, it is important that consideration be given to the growth in future traffic. Future traffic volumes can be estimated by considering the following factors:

- Historical trends exhibited by ADT and ADTT traffic volumes.
- Future highway system changes and land usage in the vicinity.
- General expected future trends in truck volumes in the vicinity, based upon economic, political, and other factors.

This information leads to the estimation of ADT and ADTT growth over some given planning period. In the past, the growth in overall ADT has averaged between 2 and 5 percent, but the growth in truck traffic growth has been much larger. This is illustrated in Table 7.3, which shows an average growth rate of 3.5 percent for all vehicles, a growth rate of 7.33 percent for all trucks, and a growth rate of 12.1 percent in the ESAL applications for several interstate routes in different states (*7,8*). If the projections are not broken out by vehicle class, this difference in the growth rates can create large errors in the estimation of future traffic loadings

Table 7.3 Example growth rates for different classes of trucks (*7,8*).

ANNUAL GROWTH RATES (PERCENT)				
LOCATION	All Vehicles	All Trucks	Trucks 5 Axle	18 Kip ESAL
I-94, MT (Wilbaux to ND)	3.4	5.4	6.3	10.3
I-90, MT (Billings to Laurel)	4.0	8.1	13.1	18.9
I-90, MT (Butte)	2.6	4.2	9.9	N/A
I-90, MT (Superior West)	3.9	9.5	10.4	10.4
I-90, WA (Cle Elum)	2.1	N/A	5.6	8.5
I-5, WA (Vancouver to Olympia)	3.6	N/A	10.1	13..
I-5, OR (Ashland)	4.1	8.8	11.7	12.6
I-84, OR (Oregon-Idaho Border)	4.4	8.0	10.4	11.1
Average	3.5	7.3	9.7	12.1

Truck traffic growth may be expressed either as simple (growing by the same number of trucks each year) or compound (growing by the same percentage of the continually escalated truck volume each year). Compound growth rates are more commonly used.

VEHICLE CLASSIFICATION: Reference has been made to categorizing the different vehicles that traverse a roadway into specific classifications. While many different classification systems could be used, it is recommended that the standard classifications in the Highway Pavement Monitoring System (HPMS) be used for rehabilitation design (*3*). The HPMS includes thirteen vehicle classifications defined as follows:

1. Motorcycles (not required).
2. Passenger Cars (not required).
3. Other Two-Axle, Four-Tire Single-Unit Vehicles.
4. Buses.
5. Two-Axle, Six-Tire, Single-Unit Trucks.
6. Three-Axle Single-Unit Trucks.
7. Four or More Axle Single-Unit Trucks.
8. Four or Less Axle Single-Trailer Trucks.
9. Five-Axle Single-Trailer Trucks.
10. Six or More Axle Single-Trailer Trucks.
11. Five or Less Axle Multi-Trailer Trucks.
12. Six-Axle Multi-Trailer Trucks.
13. Seven or More Axle Multi-Trailer Trucks.

For the estimation of ESAL loadings, vehicle classifications 1 through 4 are generally ignored because their contribution is very small in comparison to that of classes 5 through 13.

7.5 Collection of Truck Weight Data

The collection of accurate and representative truck weight data is extremely critical in estimating past or future traffic loadings. Axle type and loading has a large impact on the damage done to a pavement. In fact, axle type and weight are far more critical for pavements than vehicle gross weight. Two different trucks could have the same gross weight but cause greatly different amounts of damage to a pavement, depending upon their axle configuration.

Permanent Weigh Stations: The most common source of information on truck weights is from weigh stations. These are permanent static scales, installed adjacent to a highway, that are used to weigh the trucks utilizing the highway. Results collected from these permanent weigh stations are summarized by the FHWA in a series of "W" tables, of which the W-4 table is of the most interest to design engineers. The W-4 table consists of information on truck axle loadings and the equivalent number of 18-kip (80 kN) ESAL applications (*3*).

However, several deficiencies exist with the use of data from permanent weigh stations. First, the number of stations in any given State is limited. According to a recent survey, the number of weigh stations varies from a low of 5 in one state to a high of 64 in another, with an average of 15 locations per State (*9*).

Second, few permanent weigh stations operate continuously. Some are open only on weekdays or only during daylight hours, while others that operate on a 24-hour basis may do so only for one or two days per week. Thus, the data collected represents a very limited sample of the actual truck loading. Furthermore, numerous studies have demonstrated that the truck weight distribution varies significantly by the time of day, by the week, by the month, and by the season (*7*). Thus, adjustments to the data collected must often be made.

Finally, it is well known that overloaded trucks can bypass weigh stations by selecting an alternate route, or by traveling during periods when most stations are closed. Therefore, the data collected may not be representative of the actual loadings that the pavement is experiencing.

Portable Static Scales: Portable static scales are often used by agencies to collect site-specific information for rehabilitation design purposes. The fact that the data is collected on the pavement under consideration makes it more applicable and useful, but the data is plagued by many of the same problems that afflict the data collected by permanent weigh stations. Primarily, this is the fact that the data represents a very limited sampling that may not be representative of the actual conditions. That is, the data may only represent a short time period that would require weekly or seasonal adjustments, and the data again may not include overloaded vehicles, since truckers quickly learn of portable scale set-ups and can easily avoid them.

Weigh-in-Motion (WIM): WIM scales are an important advancement in the traffic monitoring area. In existence for over 20 years, WIM scales are devices that are installed on a roadway and record the dynamic axle weights of vehicles as they travel at highway speeds. While most WIM scales are portable, permanent scales are occasionally installed.

WIM offers a high degree of flexibility in data collection and reporting with the use of high-speed digital processors. WIM devices can be installed in each lane of a multi-lane facility to provide a distribution of the loadings and traffic in each lane.

The primary advantages of WIM include:

- Elimination of truck delays, as trucks travel at highway speeds (this may be of particular importance for high-volume, urban roadways).
- Minimization of trucks bypassing scales, as there is some concealment of the devices (and they are usually not used for enforcement).
- Increase in safety by eliminating need for slow moving traffic.
- Ability to process a large number of vehicles.
- Reduction in weight data collection costs.
- Improvement in the quality and quantity of weight data.

As previously mentioned, the truck factor calculated from WIM data is believed to be more representative of actual loading conditions than the W-4 tables, since a lot of overloaded vehicles bypass permanent weigh stations.

There are several types of WIM devices currently in use. Among the different devices are (*10*,*11*,*12*):

- *Bridge weighing devices*, in which the active weight sensing device (strain transducer) is clamped or permanently fixed to the longitudinal support beams of a highway bridge. These systems may either be portable or permanent, with the portable system requiring about 30 minutes to set up. One manufacturer is Bridge Weighing Systems, Inc.
- *Capacitance pads*, in which three layers of steel separated by soft rubber make up the weight sensors. Capacitance pads are quite portable and can be installed in 30 minutes, although they should not be installed on wet or damp pavements. Golden River Corporation and Streeter Richardson Corporation are manufacturers of capacitance pads.
- *Hydraulic load cells*, in which two rectangular platforms containing a central oil-filled piston (sensing element) are permanently affixed to the pavement in the wheel cells. Set-up time is approximately 30 minutes. CMI-Dearborn is one manufacturer of this type of device.
- *Strain gauge load cells*, in which electrical resistance strain gauges are mounted on a load plate support. This system is available as either a permanent or portable installation. Manufacturers of this device include the Streeter Richardson Corporation, the Radian Corporation, and the Siemens-Allis Corporation.
- *Strain gauge bending plates*, in which steel plate load sensors are used to measure strain under load. This type of device is usually permanent and is marketed by the Siemens-Allis Corporation.
- *Piezoelectric cables*, consisting of small diameter (0.125 in [3.2 mm]) coaxial cables that generate small electrical fields when compressed. This technology is relatively new in the U.S., but preliminary results have been promising.

One question that always arises regarding the use of WIM is their accuracy. Some comparisons between WIM scales and static scales have indicated axle weight differences on the order of 8 percent and gross weight differences of 6 percent (*17*). Vehicle classification accuracy is typically on the order of 94 to 99 percent (*17*). It should be realized that the WIM devices measure a dynamic loading effect from the passing trucks that, due to road roughness and truck suspension systems, will be different than the static truck weight. At lower speeds or on roads with an extremely smooth profile, better agreement is expected between the dynamic and the static weights.

7.6 Components of a Monitoring Program

To obtain accurate data for use in determining existing and projecting future traffic loading, a comprehensive weighing program should be in effect to provide the following information (*3*):

- Truck volumes by truck classification.
- Volume growth rate for each truck classification.
- Truck factors for each truck type and its growth rate over time.
- Lane distribution for the truck traffic, preferably by truck type.
- Variations in the average weight of each truck type by lane.
- The percentage of ESAL applications occurring during all months.

Development of Truck Factors: The weight data collected from the traffic-monitoring program is used to develop truck factors, as described previously. Load equivalency factors are employed to compute the amount of damage done by each axle load and type in terms of a standard 18-kip (80 kN) single-axle load. Then, since the number of 18-kip (80 kN) ESAL applications and the number of trucks weighed are known, an appropriate mean truck factor can be computed. It is recommended that truck factors be developed for each individual vehicle classification, instead of using a gross truck factor that reflects all vehicle classifications. This will be more accurate for the projection of future ESAL applications because the vehicle classifications can be directly considered for each highway.

Some highways exhibit much greater truck weights in one direction than in the other. For example, a major highway leading to an aggregate pit would have heavily loaded trucks coming out of the pit and empty trucks returning. Another example might be a large ocean port facility where heavily loaded trucks are carrying products to the port, but returning much more lightly loaded. Such imbalances must be accounted for in the development of appropriate truck factors.

Growth in Truck Factor: It was noted previously that truck factors have increased over many years, primarily because of increased legal weight limits and more efficient utilization of trucks. It is expected that these truck factors will continue to increase and it is important that these increases be considered. As with the truck volume growth factors, either simple or compound growth can be applied, with compound growth rates being more commonly used.

Historical data on truck weights and truck factors should provide some indication of the growth in truck factors. The growth in the truck factor should be estimated for each vehicle classification in order to obtain a more representative estimate of future traffic loadings.

Directional Distribution: The directional distribution (DD) is the percent of truck traffic traveling in one direction. Since the ADT or ADTT are normally reported as traffic in both directions, it is necessary to compute the value for each direction of travel. In most cases, it is reasonable to assume that 50 percent of the truck traffic is traveling in each direction (i.e., DD = 0.50). For a few situations, more trucks may be traveling in one direction than the other. Traffic count data collected should indicate any bias in directional truck travel, and the direction having the higher truck volume should be considered the design direction.

Lane Distribution: Just as the traffic may vary by direction, it will also vary across lanes on multiple-lane facilities. For example, the outer lane of a four-lane Interstate highway (two lanes in each direction) will carry a higher proportion of truck traffic than the inner lane. Thus, that outer lane will also carry a larger number of the 18-kip (80 kN) ESAL applications. The actual distribution of truck traffic across lanes varies with the roadway type, roadway location (urban or rural), the number of lanes in each direction, and the traffic volume. Because of these many factors, it is suggested that lane distribution be measured for the project under consideration.

In lieu of project-specific data on the lane distribution, tables have been developed. However, these tables should be applied with caution, as they are rough guidelines only. Note that a lane distribution adjustment is not necessary for a two-lane highway (one lane in each direction), since all of the trucks in each direction can only travel in one lane.

7.7 Simplified Calculation of ESAL Applications

SIMPLIFIED ESAL CALCULATION PROCEDURE: It is sometimes useful for the design engineer to obtain a quick approximation of the past or projected number of 18-kip (80 kN) ESAL applications for the highway under consideration. To do this, a simplified calculation procedure can be used. The procedure is termed "simplified" because it uses an *average* truck factor instead of a class-specific truck factor. As such, results obtained using the simplified procedure may not be accurate. This simplified procedure to compute ESALs is often used in Pavement Management Systems

The 18-kip (80 kN) ESAL estimate using the simplified procedure may be computed from equation 7.2. All of the required inputs for that equation were described in the preceding section. To illustrate the use of the simplified procedure, consider the following example:

Assume a four-lane Rural Interstate Highway

Initial ADT (two-way) = 30,000

15 percent heavy trucks (class 5 or greater)

Current Truck Factor = 0.84

Directional Distribution = 50 percent

Lane Distribution = 80 percent

Truck Volume Growth Rate = 4 percent

Truck Factor Growth Rate = 2 percent

Estimate: The number of 18-kip (80 kN) ESAL applications for a 5-year planning horizon.

To assist in determining the number of 18-kip (80 kN) ESAL applications, it is convenient to set up a spreadsheet to help perform the calculations. For this example, a table has been set up (see Table 7.4).

A total of 3,116,968 18-kip (80 kN) ESAL applications are estimated for the roadway under consideration. The yearly ESAL is equal to the ADTT x DD x LD x TF x 365 (days in a year).

These values are then summed in the cumulative column to come up with the estimated traffic loading.

Table 7.4

Year	ADTT	DD	LD	TF	Yearly ESAL*	Cumulative ESAL*
1	4,500	0.5	0.8	0.840	551,880	551,880
2	4,680	0.5	0.8	0.859	586,938	1,138,818
3	4,867	0.5	0.8	0.874	621,049	1,759,867
4	5,062	0.5	0.8	0.891	658,495	2,418,362
5	5,264	0.5	0.8	0.909	698,606	3,116,968

**One direction, outer lane.*

7.8 Factors Affecting the Accuracy of ESAL Calculations

There are a number of factors that affect the calculation of the 18-kip (80 kN) ESAL applications. It is important for the design engineer to be aware of these factors as estimates of traffic loadings are developed. The following is a description of some of the more important factors that influence the ESAL calculation.

Load Equivalency Factors: Load equivalency factors play a fundamental role in the estimation of traffic loadings. However, these factors are based on the results of the AASHO Road Test, which was conducted over 30 years ago. Truck characteristics (axles, suspension systems, tire pressures) all have changed since that time, and it is not known how applicable the factors are to today's trucks. Furthermore, the results represent data from only 2 years of traffic loadings (a maximum of about 1 million load applications), far less than what today's pavements experience. How the factor changes with time and how it is affected by the environment are not known.

One study has shown that the LEFs are not constant, but are strongly dependent upon the pavement condition (*6*). As the pavement deterioration increased (serviceability decreased), a large increase in the LEF was observed. Another study has indicated that LEFs are influenced by the subgrade stiffness, and suggested that seasonal LEFs be considered (*8*).

Finally, as previously mentioned, the LEFs are based on serviceability loss, not pavement distress. As there is more movement toward mechanistic design procedures in which pavement stresses and strains are related to pavement damage, the ultimate applicability of the AASHTO LEFs is unknown.

Composition of Traffic Stream: A traffic stream is composed of different types and weights of vehicles. Each vehicle, because of its axle configurations and weights, inflicts a different amount of damage to the pavement. The damaging effects done to the pavement structure by automobiles and light trucks are generally so small that they can be ignored. However, the impact of trucks on the ESAL estimate is quite substantial, and that makes it essential that accurate counts of heavy truck traffic be collected.

Truck Factors and Axle Weights: Historical trends have shown increases in the truck factor (ESAL/truck) for all classes of commercial trucks. This can be attributed to increases in legal axle weight limits and increased utilization of trucks so that fewer "empty runs" are being made. Therefore, the collection of representative axle weight data, from which the truck factors are developed, is essential to the development of accurate truck factors. Furthermore, it is important that truck factors be developed by truck classification and not averaged across many classifications. Weight data collected using WIM devices are believed to be more representative of actual loading conditions.

Axle Configurations: It has been shown that a 36-kip (160 kN) single axle does much more damage to a pavement than a 36-kip (160 kN) tandem axle, even though the gross load on each axle type is the same. Thus, there are clearly some benefits to distributing truck weights over many axles. As gross loads continue to increase, different axle configurations are being used to maintain the per axle load in the same range as before. However, this practice does not guarantee a similar rate of deterioration in the pavement.

The appearance of the tridem axle is one indication of a newer axle configuration that is now in use. Other trucks with multiple axle combinations have appeared that carry large gross loads distributed over many axles. One study has suggested that the AASHTO LEFs underestimate the damaging effect of dual and triple axles in comparison with single axles (*13*).

7.9 Truck Flows and Loads for Pavement Management

The remainder of this module is devoted to the basic requirements for the development of a truck flow map or ESAL traffic load file for use in pavement management systems. This last section of this module recommends procedures that highway agencies can use to determine the location and frequency of their truck monitoring activities. The objective of the recommended procedures is to help an agency design a program that cost-effectively meets its needs for truck traffic load data within its overall pavement management structure. If the data are collected and used properly, they should provide a much more effective pavement design and management process than is currently available, thereby increasing the reliability of pavement designs; decreasing overall pavement construction, maintenance, and rehabilitation costs; and improving an agency’s ability to manage its pavement infrastructure.

This section discusses:

- Procedures required to determine the number and distribution of continuous, automatic vehicle classification (AVC) and weigh-in-motion (WIM) devices within an agency,
- A system for using the data gathered with these devices to adjust data from short duration vehicle classification and WIM counts to better estimate average annual conditions,
- The appropriate length of short duration AVC and WIM counts required to develop annual average estimates of travel within specified levels of precision, and
- Research performed in Florida and Washington that illustrates the variability of vehicle classification and truck weight data that states can expect to find on their roads.

The general recommendations presented in this module are based on a series of analyses performed with WIM data from Florida and WIM and vehicle classification data from Washington (*14,15*). This section of Module 7 has been largely extracted from the Final Report from Research Project T9233, Task 16 “Truck Flows and Loads *16*) by Mark Hallenbeck and Amy J. O’Brien from the Washington State Transportation Center.

7.10 Variability in Truck Travel Patterns

The analyses performed by Florida and Washington showed that different states are subject to different truck travel patterns. Some states (and even some portions of some states) are subject to truck travel that varies throughout the year as we briefly mentioned in previous sections of this module. Other states have fairly stable truck volumes, with little variation from season to season. In some states, truck volume and weight patterns are fairly consistent for all roads. In other states, truck volume and weight patterns vary considerably among roads and among geographic areas.

The key to determining (and thus improving) the accuracy of pavement loading estimates is in determining the variability inherent in the data and then measuring how much of that variation is accounted for by the data available for making an estimate.

This section examines the variability found in the volumes and weights of trucks in Florida and Washington.

These two states discovered differing amounts of variability in the trucking patterns in their states. In general, Florida had more stable truck patterns than Washington. However, even within Florida, a considerable amount of variation was apparent.

Site Specific Variation: Variation in both truck weights and truck volumes were present in four major areas:

- Time of day
- Day of week
- Season of the year
- Geographic location

Time of Day Variation: The time of day variation is usually accounted for in both WIM and vehicle classification estimates by collecting data for 24-hour periods. Neither the Florida nor Washington analyses explored these within-day variations because the data used for these analyses incorporated data collection through the day. However states that use partial-day counts to represent 24-hour totals must understand that truck traffic varies throughout the day and that truck time-of-day patterns are different than automobile patterns.

Day of week: Variations differ from state to state, and from site to site within an agency. The analysis of Washington vehicle classification data showed that truck volumes on Tuesdays, Wednesdays, and Thursdays were statistically the same. For some roads, truck traffic on Mondays and Fridays was also similar to that on Tuesdays through Thursdays. In other locations, Mondays and/or Fridays were statistically different. At almost all sites, Saturdays and Sundays experienced different traffic patterns than those of weekdays. (In addition, Sundays were different than Saturdays at most sites.)

The study also found that truck volume day-of-week patterns were not similar to automobile day-of-week patterns. Finally, the day-of-week patterns for many truck types differed as well. For example, in Washington, many sites experienced such a large drop in heavy truck traffic over the weekend that the average monthly weekday traffic volume for large trucks for all 12 months of the year was greater than average annual conditions. (In other words, if trucks were counted on any given weekday during the year, the number of trucks counted times 365 would exceed annual truck traffic on that road.) If the annual estimation process does not account for day-of-week changes such as the decrease in truck volumes observed in Washington, those annual estimates will include significant errors. Consequently, the prediction of annual average conditions must account for the different traffic levels that are present on different days of the week.

Season of the Year: Truck patterns also change by season in some locations. Florida examined the seasonal patterns of WIM data and concluded that little seasonal variation was present in that state. A brief analysis of Washington data showed a considerable amount of seasonal variation among the WIM patterns at ten sites in Washington. The different results from both analyses are not surprising. The presence of seasonal variation within an agency is a direct result of the types of commodities trucks carry in that state and the movement patterns of those commodities. Common sense predicts that roads in different parts of the country will experience a variety of truck travel patterns, and indeed seasonal differences have also been observed in examinations of WIM data in Minnesota and Pennsylvania.

For example, in south central Washington, a considerable increase in both truck volumes and average damage factor per truck type occurs in the late summer and early fall as a result of agricultural movements. Florida also has agricultural commodity movements, but the greater diversity of crops and year-round growing season in Florida have resulted in a more continuous truck movement throughout the year, rather than the peaked pattern found in south central Washington.

However, the late summer/early fall peak movement described above is not found west of the Cascade mountain range, because this section of Washington is more urban. Furthermore, in the rural areas of the western portion of Washington, the truck volume patterns are very different than those found in the south central portion of the state.

Geographic Location: It is also possible to find two roads near each other that have very different truck patterns. For example, roads impacted by heavy through truck traffic movements may have very different truck volume patterns than roads that carry primarily local traffic.

Florida determined that most principal arterials in the Panhandle region followed similar vehicle weight patterns. Of the four WIM sites in that group of roads, three of the sites had a mean damage factor for single trailer trucks of between 0.66 and 0.68. However, the fourth site had an average damage factor of 1.75. Differences of this size can be caused by the location of specific facilities (e.g., a gravel pit), the nature of truck hauls on a specific facility, or the presence of other mitigating factors.

These findings support the generally held belief that truck volume and weight patterns are heavily influenced by factors such as weather (particularly where weather requires the imposition of load restrictions), type of truck hauls, local industrial base, the amount of through-traffic, and other factors. As a result, the truck patterns that any state or any site within an agency will experience will vary according to local conditions. The truck patterns in one state may bear very little relation to those in a neighboring state, and thus each state will need to investigate the variation of truck travel on its own highway system.

Group Mean Variation: One of the findings of both the Washington and Florida studies was that the mean for a group of related sites can be significantly different than the actual value for a specific site or route. For example, in Florida, the mean damage factors (computed as ESALs/vehicle) for 3S2 trucks for I-75 at four sites were computed as 0.97, 1.31, 1.34, and 1.57. Similar variability in damage factors per vehicle was found in the Washington WIM data; average damage factors at three WIM sites on I-5 ranged from 0.825 to 1.75.

The variability described above illustrates the importance of determining and accounting for the variability in truck characteristics (volumes, vehicle classifications, and weights) found in all states. For example, using the smallest damage factor in determining pavement design for the highest damage factor location will lead to premature failure of the pavement. Using the largest damage factor for a smaller damage factor location will result in substantial over-design of the pavement structure. Even the use of the mean for the four sites will result in over-design of the pavement at one location and premature failure at the other.

Different proportions of vehicles within the different vehicle classes will accentuate the variability in damage factors. For example, in the Washington data, the proportion of 3S2 trucks in the traffic stream ranged from 2.5 percent at one site to 20 percent at another site. Even within the stream of trucks itself, the proportion of specific types of trucks varied. At some Washington urban sites, single trailer trucks made up less than 20 percent of the total truck traffic. At other (rural) Washington sites, single trailer trucks made up as much as 75 percent of the total truck traffic.

In the Florida WIM data, the proportion of 3S2s in the truck traffic ranged from 19 percent at one site to 84 percent at another site. Florida and Washington urban areas normally experience a considerably higher proportion of small trucks, and rural areas normally experience a higher proportion of larger trucks. As a result of these differences in vehicle mix, the average damage factor per truck can differ from site to site, even if the average damage factor per truck type does not. Remember that the average damage factor per truck of each type can also change, as noted earlier.

It is because of the variety of ways in which truck volumes and loads vary over time and from site to site that accurately predicting loads is a difficult task. Recommendations for accounting for this variation are presented in the remainder of this report.

7.11 Recommended Data Collection System

Because of the potential for variation in the number and types of trucks, as well as in the damage each truck causes, site specific data collection is the best method for gathering accurate truck volume and weight data for pavement design and management. Unfortunately, the cost of collecting these data is high, and the collection of data at all sites is not realistic. WIM data, in particular, are difficult to collect. The reasons are that the collection of accurate loading data requires pavement conditions that are not present in many roadways and that the sensors needed for WIM data collection are not easily placed in the pavement.

Therefore, the basic data collection methodology recommended is to collect site specific data whenever possible and to supplement these data with data collected at continuously operating sites at a more limited number of locations. The continuously collected data provide an understanding of truck travel variation over time, while the short-term data supply the geographic distribution needed for an agency’s pavement management system.

This recommended system for determining vehicle loadings for an agency's PMS does not change the basic philosophy underlying the computation of pavement loadings in most states. The recommended system still computes total load by using vehicle classification counts to estimate the volume of vehicles by class, and WIM data to estimate the average damage factor by vehicle class. The primary change for most states is the adjustment of truck volumes and loading for variation in truck travel by day of the week and/or season of the year.

Unfortunately, there is no simple formula for determining the “optimum” number and distribution of long- and short-term data collection efforts. Each state must develop these numbers by balancing its need for information against the resources required to collect that information. The number and distribution of counts required by a large state with diverse traffic characteristics will be very different from those required by a small state with homogenous traffic characteristics.

The data collection program is designed to produce two types of estimates, site specific values and “system” or “group” means. Note that the definition of a “system” or “group” will vary from state to state. For most applications, site specific estimates are better than system means. However, as indicated earlier, the collection of site specific estimates is often unrealistic because of limited resources, and where this occurs, system means must be used.

SITE SPECIFIC DATA: The first recommendation for improving loading estimates is to use data specific to each pavement site whenever possible. Research has shown that truck-loading rates (both the number and weight of trucks) can vary considerably from road to road, even within a specific geographic area. The collection of either (or both) vehicle classification counts or weigh-in-motion data at a site for which loading rates are being computed will dramatically improve the accuracy of the loading rate estimates used for pavement management system analyses and pavement design. The more site specific loading information collected at a site, the better will be the annual load estimates.

AVERAGED DATA: Because traffic data collection, particularly WIM data, is expensive, little or no site specific data will be available for developing pavement loading rates. Where site specific information is not available, values for "similar" roadways must be used.

The use of “similar” roadway values for estimating the number of trucks on a road is highly discouraged for actual pavement design. These values should only be used for network level estimates when the cost of data collection prohibits the collection of site-specific data.

However, the use of “similar” roadway values for estimating vehicle weights is often necessary because of the difficulty and cost of placing and operating portable WIM equipment. Where site specific WIM data are not available to provide damage factors for the trucks that are using the road, average damage factors for other “similar” roads must be used. When these average damage factors are developed, *the best estimate is the mean damage factor per truck type for a sample of roads that are assumed to carry similar truck traffic.*

The accuracy of these “similar road” estimates is dependent on each state's ability to define "similar" roads. Having roads that are truly alike

- Reduces the variability of truck characteristics between roads in each group,
- Improves the state's ability to measure the true population mean for that group of roads, and
- Reduces the differences between the specific site in question and the true group mean.

7.12 Design of a Continuous Data Collection Program for Vehicle Classification and Weight

The design of the long-term (i.e., continuous) data collection system for both vehicle classification and truck weights (leading to damage factor estimates) relies on a combination of both statistics and professional judgment. Few (if any) states have sufficient amounts of vehicle classification or truck weight data to accurately describe the true population of truck patterns for all roads in their state. Thus, some professional judgment is needed to make the assumptions that drive the statistical equations used by this methodology.

As described previously, both the vehicle classification and weigh-in-motion data collection programs need to account for all four types of variation in truck travel patterns. To eliminate errors from time-of-day variation, the recommended data collection process uses 24-hour truck traffic counts and average daily damage factors. In order to perform quality control checks, the authors recommend collecting data as hourly volumes by vehicle classification and either individual vehicle weight records or hourly summaries of vehicle volumes and weights. After the quality control checks, these data should be aggregated into 24-hour totals (class data) or averages (damage factors per vehicle class).

To account for both day-of-week and seasonal variation in vehicle classification and truck weight data, the data collection program should have some sites that collect data year-round (at least for a few years). Besides helping to determine the types of seasonal and day-of-week patterns, these continuous stations provide the data necessary for estimating the number of data collection counts required to provide annual estimates at a given level of accuracy.

NUMBER OF CONTINUOUSLY OPERATING WIM SITES NEEDED: The number of continuously operating sites that are needed will vary from state to state, depending on the variability of truck traffic and the accuracy with which the state wishes to estimate average damage factors and other group statistics. The greater the variability of truck patterns is within an agency (either seasonal or geographic), the greater is the number of sites required. The more homogeneous the truck traffic is, the smaller is the number of continuously operating sites required.

Step 1 - Create Groups of Roads: The first step in determining the number of continuously operating sites necessary for both vehicle classification and truck weight is to divide the state into basic groups of roads that the DOT believes contain reasonably homogeneous truck populations and patterns. (This must be done with professional judgment, based on the information available to the state.) In Florida, road groups were defined by both geography and functional classification. (Florida developed 18 groups. Four of these were individual interstate highways; the remaining seven geographic areas were split into principal and minor arterials.)

These groups of roads do not have to be the same for vehicle classification and truck weights. That is, the state may aggregate roads into one set of groups for truck volume patterns and a different set of groups for truck weights. Both of these groupings may be different from the roadway groupings used to factor volume counts. (Note that the same sites may be used, they are just grouped differently for classification than for weights.)

The more alike the roads are in a group, the fewer are the data collection points that will be needed within that group to accurately estimate the mean population statistics for that group. The more diverse the roads within each of those groups, the more data collection points will be needed. At the same time, generally, when more groups are present, more total sites are needed to measure mean values within a given level of precision. (The best rule of thumb for selecting groups is that if a large group can be divided into two or more smaller groups that have much lower internal variability the large group should be split. Using statistics to determine whether two groups of sites are statistically different is a good method of determining whether two groups of roads should be aggregated together or left separate.)

Some states may have only one group (all roads in the state). Other states may have a large number of groups, needed to track a number of different travel patterns. If Estimates of truck weight variability are representative of the variability typically found in the nation. Between 5 and 15 sites will be needed per group to develop mean damage factors for each group to achieve a precision level of ± 10 percent, 95 percent of the time within that group.

Step 2 - Determine Homogeneity of Groups: Once the state has developed initial road groups, it must determine whether the roads in the group really have similar travel patterns. To do this, the state must examine the patterns observed in the available data. For example, for truck weights, are the mean damage factors for 3S2 trucks (or single trailer trucks) roughly the same? Plot the daily damage factors for these vehicles over time and compare the plots for different sites within each group. If the travel patterns observed in these plots are similar, then the groups are relatively homogenous. If they are not, refine and retest the road groupings.

There are no statistical absolutes that dictate how “tight” a group must be (i.e., how little variation between sites it must have). For damage factors per truck, it has been recommended that users calculate the average annual damage factor for either the 3S2 (FHWA Class 9) or single trailer truck categories (FHWA Classes 8, 9, and 10 combined) for each site, and using this as the decision making variable. If other truck classes cause a greater proportion of road damage for that group of roads, use that most important vehicle class.

The average annual damage factor at each site must incorporate any differences that exist between weekday and weekend loading rates, as well as variations throughout the year. These values are most commonly developed by averaging a year of data, although samples of data from a year can be used instead, with some loss of precision. Once the average annual damage factor for each site has been computed, calculate the mean and standard deviation of these values for all sites within each roadway group. The standard deviation of this factor provides an initial measure of “how good” or

Step 3 - Determine the Number of Sites Required: These two values are also necessary for determining the number of sites that are required for each group of roads to meet desired levels of precision.

The following equation is used to determine the number of sites required (*2*):

Equation 7.3

$$\mathbf{n} = \left[\frac{t \ * \ \mathbf{COV}}{\mathbf{d}}\right]^{2}$$

Where Alternatively, the equation can be written as:

$$\mathbf{n} = [\ (Z)(F)/\ d]^{\ 2}$$

Where:

n =	Number of sites required
Z =	the Z-score associated with the desired level of confidence
t =	Student’s t statistic for n- degrees of freedom
F =	the standard deviation of the group damage factors
COV =	coefficient of variation for the damage factor within the sample
d =	the desired precision or allowable error expressed as a fraction of the mean damage factor

Use of this equation is justified by the Central Limit Theorem when the number of sample sites selected exceeds 30. This formula will require slightly fewer sites than Equation 7.3 to achieve a given level of precision. However, if fewer than 30 sites are used to calculate the coefficient of variation, the distribution of those sites is often not normally distributed, and the Z statistic does not accurately predict the distribution of the population as a whole.

Thus, the greater the precision or the coefficient of variation of the damage factors that is desired, the larger is the number of data collection points required.

Several significant assumptions are made when this formula is used. These are described below.

Assumption 1: The damage factors within each roadway group are normally distributed about the mean value. If they are not normally distributed, this equation is inappropriate.

Assumption 2: The limited number of sites available for calculating the standard deviation of the damage factor are representative of the population of roads incorporated in the group. This second assumption causes the error associated with damage factor calculations to be underestimated. Often, only two or three WIM sites exist in any one roadway group. As a result, these sites must represent many roads that experience a variety of truck travel characteristics. For example, if the two or three WIM sites present have similar damage factors, the above equation will indicate that few sites are needed to estimate the mean value. Error will result if some of the roads in the group actually have much different damage factors. An example is the Florida Panhandle area described earlier. If the site with a damage factor of 1.75 were not present, the truck damage factors for the roads in the panhandle would appear to have very little variability. By adding this one specific station, the expected variability within the Panhandle would increase dramatically, and the number of sites needed to estimate the true mean damage factor would increase accordingly. The opposite type of error can occur when most roads in a group have similar characteristics, but the roads selected for weighing contain highly variable characteristics. In this case, the number of sites needed will be over-estimated. This type of error often occurs with WIM data because the cost of WIM data collection limits the geographic distribution that can be achieved with the available resources. Because WIM data collection is limited, it is usually difficult to accurately determine these values.

Assumption 3: The third assumption of Equation 7.3 is that the damage factors used in the calculation are the “true” mean damage factors for each site. That is, this equation assumes that the damage factor used for each site has no error associated with it. (The WIM device is assumed to have operated correctly for 365 consecutive days.) However, if data are not available for an entire year, additional error is associated with this equation for which the statistical theory used to derive the equation does not account. This additional error can not be easily calculated. If the damage factors from each site are reasonably accurate and the estimates used contain no bias, this error is small. However, if the data do contain bias, this error can be significant.

In the Florida WIM data analyses, Florida DOT determined that annual average damage factors for sites with "heavy" seasonality can be estimated within ± 10 percent with 95 percent confidence (for a particular site) if four week-long WIM counts are conducted during the year. These four counts should be spread equally throughout the year. At sites that have moderate seasonality, this level of precision can be obtained with two weeklong WIM counts. If there is no discernible seasonality, one weeklong count is sufficient. These estimates need further testing in other states.

Assumption 4: The final assumption required to use Equation 7.3 is that the precision being measured is actually the error associated with calculating the mean for the roadway group. However, when this estimate is applied to a specific site there are two sources of error. The first source of error is the calculation of the mean value for the group. (This is the value given in Equation 7.3 as “d”, given the above assumptions.) However a second, much larger error is the error associated with applying a mean value to a specific geographic location (i.e., the geographic variability).

The site at which the mean value is applied is really only one of many sites within the roadway group. This group of sites has a diverse group of damage factors. That group of damage factors forms a distribution about the true mean for the group (an estimate of which is calculated above). The actual damage factor for the site at which the mean is applied can fall anywhere within that distribution. Without site specific information, its location within the distribution can only be predicted as being within a given number of standard deviations of the population mean. For example, the true value for the site in question will be within one standard deviation of the mean 68 percent of the time if the group of roads has a normal distribution. The value of this standard deviation is the same as that used in Equation 7.3.

The number of samples computed in Equation 7.3 has no impact on the precision of the mean value as it is applied to an unsampled specific site. The lack of effect that sample size has on the precision of the mean value at a specific point is a result of the geographic variation in truck patterns and the lack of site specific information, not the size of the sample taken to predict the mean population value. The only way to improve the precision of damage factor estimates at a specific site is to collect WIM data at that site. Data collected at the site in question have no geographic component of variability (although they do have seasonal and day of week variability).

Number of continuously operating Vehicle Classification Sites Needed: The same process can be repeated for vehicle classification estimates if the value predicted for vehicle classification is a mean for a group of roads. Unfortunately, pavement engineers rarely need the mean volume or mean percentage of trucks for a group of roads. Instead they need the volume of trucks (or the percentage of trucks) by vehicle class at a specific site. As a result, the mean volume for a group of roads is considerably less useful than the mean daily damage factor per truck for those roads.

In most cases, truck volume estimates are based on site specific or nearly site-specific vehicle classification counts. This site specific counting is the most important aspect of pavement loading estimation, because the volume and type of trucks at a site is much more variable than the load per vehicle, and plays such an important role in the determination of total loading. (Sometimes these counts are too old and/or too far away from the site being investigated, but that is a different problem.) Because these counts are taken at the site in question (or at least close to the site in question) little or no error is associated with the geographic component of variability. However, the use of short duration counts to estimate average annual conditions is still subject to errors caused by seasonal and day-of-week fluctuations in truck volumes.

Thus, roads still need to be grouped to assist in estimating seasonal and day-of-week truck volume fluctuations. Using average patterns obtained from road groups to adjust site specific counts is one way to reduce the impact of seasonal and day-of-week fluctuations, and improve the accuracy of annual traffic loading estimates. Because truck volumes are normally more variable than damage factors per truck, a larger number of continuously operating classifiers is generally needed than continuously operating WIM scales.

As with the application of average damage factors per truck two sources of error are associated with the application of average seasonal and day-of-week adjustment factors. The first source of error is prediction of the average seasonal adjustment factor. The second source of error is the difference between a specific site and the mean of the group of roads to which it is assigned.

Guidance for developing groups of roads, determining the number of data collection sites that should be operated for each group of roads, and computing and applying seasonal factors on the basis of these groups is provided below.

The “classic” process for determining the roads that should be grouped together and then determining the accuracy of the specific adjustment factors developed for those roads is similar to that for truck damage factors described earlier in this document.

Step 1 - Calculate Seasonal and Day-of-Week Adjustment Patterns: The first step is to calculate the seasonal and day-of-week adjustment patterns for all sites within an agency that have the appropriate data. (Sites to be used in this effort must have continuously operating WIM or vehicle classifier equipment functioning for at least one year.) To simplify the factor process, the day-of-week and seasonal adjustment patterns should be combined into one factor. In Washington, a short count taken on a weekday is divided by a seasonal factor that is the ratio of Monthly Average Weekday Traffic (MAWDT) for the month in which that count was taken divided by the Average Annual Daily Traffic (AADT). A weekday is assumed to be any 24 consecutive hours of counting between noon Monday and noon Friday. The math for this factoring process is shown in Equation 7.4.

Equation 7.4:

$$\text{AADT (by class)} = \frac{\text{24-hour weekday short count}}{\text{(MA WDT/AADT)}}$$

Where more than one weekday of data is available, the daily counts are averaged before they are divided by the MAWDT / AADT ratio. Therefore, in Washington the seasonal pattern to be computed in this early step are the 12 monthly ratios of MAWDT / AADT.

Step 2 - Create Groups of Roads: The next step is to use professional judgment to initially estimate how roads in the state should be grouped so that each site within a group experiences relatively similar truck volume patterns. These road groups may be very different from both the traditional volume seasonal factoring groups and the damage factor groups discussed above. They may even vary for different classes of trucks.

As with the damage factor road groups, each state may divide itself into different road groups on the basis of state specific criteria. The most common criteria used are geographic location, functional classification of roadway, and some measure of recreational activity. A measure of economic activity (e.g., farming area or a coal mining area) may also be needed to describe the expected truck volume patterns. However, the factors that are important in one state for differentiating truck volume patterns may be very different from those that are important in another state.

Step 3 - Determine Homogeneity of the Groups: Using the seasonal/day-of-week patterns for all available sites, it is possible to determine the acceptability of these initial road groups by computing the mean and standard deviation of the monthly factors for each month for each proposed group of roads. Performing these computations, will make apparent the fact that variability of truck travel is much higher than automobile travel variability. The analyses performed with Washington data showed that peak season adjustment factors for many truck types were routinely around 1.6 for the ratio of MAWDT/AADT, with adjustment factors greater than 2.0 for highly variable sites. For sites where volumes of trucks were low (e.g., sites with average daily volumes of less than 50 vehicles in a particular truck class) factors considerably larger than 2.0 were occasionally present. Similar adjustment factors for automobiles were rarely higher than 1.3 or 1.4, with adjustment factors of 1.6 or 1.8 for extreme recreational routes.

Since truck adjustment factors tend to be quite high (and sometimes quite variable from year to year or from vehicle class to vehicle class), the standard deviation of the monthly seasonal factors within the proposed road groups is likely to be high. This is true particularly in comparison to the standard deviation for automobile seasonal factors. The higher is the standard deviation of these factors, the greater is the number of data collection sites needed to estimate the mean monthly factors for each group of roads within a given level of precision. (It is assumed that each of these sites is a permanent data collection device, collecting data year-round.)

Step 4 - Determine the Number of Sites Required: As with truck damage factors, the number of sample sites needed to compute the mean group factor can be computed with Equation 7.3.

The value for n in Equation 7.3 <u>includes</u> the WIM locations computed in the previous section, as long as those sites collect vehicle classification data throughout the year. When calculating the number of sites, note that each month of the year will have a different mean and standard deviation for each road group. (That is, there will be 12 different means and standard deviations for each road group.) In addition, each vehicle classification for which a factor is computed will have a separate set of 12 monthly means and standard deviations.

To simplify the computational process, the sample size selected should be based on the accuracy of the most important truck classification. This is usually single trailer trucks or FHWA Class 9 vehicles. In addition, it should be performed for either the worst month of the year (so that the precision achieved for all months is at least as good as the sample design indicates) or the most variable month for which traffic data are routinely collected (*3*). For example, if no short duration traffic counts are taken in December, January, or February because of snow, the variability of seasonal factors during these months does not need to be considered when determining the appropriate sample size for the factor group.

Precision of the seasonal factor versus precision of the factor's application: As with the damage factor calculations presented earlier, Equation 7.3 only computes the precision of the mean monthly factor for a group. This is not the same as the precision associated with applying these factors to a specific site. Furthermore, the precision of applying a given monthly factor to a specific site can be estimated using the standard deviation of the factor for the group. That is, there is approximately a 90 percent chance that the true adjustment factor lies within two standard deviations of the true mean adjustment factor. This error is not impacted by the sample size used to compute the group mean factor. This is the primary reason why no "group factoring" approach to adjusting short duration truck volume estimates will achieve high levels of precision in the estimation of truck AADTs when even moderate levels of variability are present within a factor group. *(Note that the accuracy of the annual estimates is still improved by factoring.* The errors associated with these estimates are simply larger than commonly requested for traffic volume counts.)

Adjust the factor groups as necessary: If the standard deviation within a factor group is too high to either allow use of a moderately low sample size for calculating mean group factors, or produce the precision levels needed when applying those factors, some adjustment of the road groups may be necessary. As with the truck damage factors, the variability of factors within groups can sometimes be decreased by defining more groups. This process can decrease the number of sites needed to estimate each group factor mean within a given level of precision and increase the precision of each of those estimates when they are applied to specific sites. However, the increase in the number of groups usually requires a corresponding increase in the number of sites needed because group factors are needed for more groups. (For example, with six factor groups, an average of 10 sites per group (for a total of 60 sites) might be needed to achieve a specific level of precision. By redefining roads into eight groups, the lower variability might allow the same level of precision with an average of eight sites per group. However, 64 sites would be required for the state.)

When factor groups are developed, states should look critically at their initial assumptions of traffic patterns. Both Washington and Florida were occasionally surprised at the truck patterns observed in their data. In many cases increases in precision (and decreases in the required sample sizes) can be obtained by simply reassigning some roads from one factor group to another, rather than by redefining the entire factor group.

However, the groups selected must include some type of explanatory mechanism or roadway characteristic that defines the group. Without a good explanatory mechanism, the assignment of short counts to factor groups becomes too subjective; leading to significant bias errors.

Seasonal factors decrease bias even for groups with high variability: Guidance on how "tight" a factor group should be can also be obtained by examining the value of the mean factor being computed. If the mean factor (assumed to be MAWDT/AADT) for a vehicle class for a month is 1.6, this represents a 60 percent adjustment to the short count to estimate AADT. This adjustment is extremely large, and thus even if the adjustment is inexact, a significant improvement in the accuracy of the annual estimate will result from its application.

For example, if the standard deviation of the mean factor is 0.15, there is a 90 percent chance that the true adjustment factor at any specific site will lie between 1.3 and 1.9. If we assume that the actual adjustment for the site in question is at the extreme for this range (1.9), the application of the factor of 1.6 still reduces the error of the annual travel estimate considerably. This is illustrated below.

Short count = 100 vehicles per day

Estimated Seasonal Factor = 1.6

Actual AADT = 52

Actual Seasonal Factor = (100 / 52) = 1.9

Estimated AADT Using Short Count and Estimated Factor = 100 / 1.6 = 62.5 = 62

Error Without Factoring = (100 - 52) / 52 = 92 percent

Error After Factoring = (62 - 52) / 52 = 19 percent

Thus, while factoring with an imprecise group mean may still leave a considerable error, when the factors applied are large, *the resulting annual estimates are still considerably more accurate after factoring than before*.

In addition, the estimated AADT will be unbiased. That is, some AADT estimates (after factoring) will be slightly greater than the true AADT and some will be smaller than the true AADT. If factors are not applied, most truck AADT estimates for sites within a group will be on one side of the true estimate. (For example, in Washington, weekday counts of combination and double trailer trucks during almost any month of the year at almost any site over-estimate the AADT for those vehicle types.

In the Washington analyses, it was not possible to develop truck factor groups that routinely produced estimates of truck volume AADTs within ± 10 percent 95 percent of the time. When factor groups were developed with the above techniques, the AADT estimates significantly improved; however, the high level of variability in the truck volumes prevented the researchers from reaching the desired levels of precision.

7.13 Other Issues

Distribution of Counts Within a Group: One question that is unanswered by the previous discussions is how to distribute counts between sites within a group of roads. A variety of techniques are available for this task. From a statistical standpoint, the best method for distributing the count locations is to use a random sample.

Because WIM data collection requires good pavement conditions (smooth pavement, no horizontal or vertical curves, etc.), the number of locations at which WIM can be installed will be limited. It is appropriate to select randomly among these potential locations.

The problem with truly random distribution of a small number of sites within a group of roads is that such a distribution may not account for the geographic diversity within a group. That is, if the “group” is the entire state, and all of the count locations are in the southern end of the state, no data will indicate whether the northern end of the state experiences different truck traffic conditions. This lack of diversity in the selection of sites can also apply to other stratifications (e.g., functional class, and volume of road). The limited number of continuously operating WIM and vehicle classification counters and thus the lack of diversity in the sample makes it very easy to create.

Therefore, it is acceptable for the state to use some professional judgment in selecting data collection sites so that sites within a group are distributed roughly in proportion to the presence of roads that contain a particular characteristic within a factor group. For example, if 40 percent of truck VMT is in the northern half of the state, roughly 40 percent of the WIM sites should be in the north. However, caution must be exercised when deviating from random site selection, because subjective selection of data collection sites can also bias the data being collected (for example, towards the truck characteristics experienced on high volume truck routes, and away from lower volume routes).

A careful mix of random site selection mixed with prudent professional oversight will help ensure that states are able to detect the types of travel patterns that exist. A good rule to use when either distributing sites or checking the distribution of existing sites, is that sites should be located in rough proportion to their contribution to truck VMT in the state. That is, if interstates are responsible for 50 percent of truck VMT they should have roughly 50 percent of the sites being distributed. This same philosophy can be extended towards geographic areas (as illustrated above), or other stratifications of interest to the state.

Axle Correction Factors: The Washington vehicle classification analysis found that axle correction factors are highly variable from site to site, as well as from month to month. Weekday and weekend axle correction factors also differ significantly.

In general, at all sites, the axle correction factor measured for weekdays was higher than that measured on weekends. In addition, the difference in axle correction factors among sites was more significant than the difference between axle correction factors from one month to the next. However, the difference in axle correction factors between weekdays and weekends was often as large the difference among sites.

A single-axle correction factor for all seven days predicts too many trucks operating during the weekends and not enough during the weekdays. This prediction results in the underestimation of vehicles on the weekend and the overestimation of vehicles on the weekdays. To avoid these problems, the states should use axle correction factors that are consistent with the axle counts being factored. For example, only data from weekdays from a continuously operating vehicle classification counter should be used to compute axle correction factors that will be applied to weekday counts.

Number of Vehicle Classes That Should Be Used: In most cases, aggregated vehicle classifications should be used to develop seasonal factors. The analysis of Washington classification data showed that several of the FHWA vehicle classifications contained such a small percentage of vehicles, that for moderate and lower volume roads, the volume patterns for these classes often became unstable. (That is, small changes in volumes within some classes caused extreme changes in seasonal, temporal, and day-of-week patterns. This made it difficult to determine consistent travel patterns within these vehicle classes.)

The authors of the Washington report conclude that from four to six vehicle classes should be used for seasonal factor development for moderate and lower volume roads. Use of a smaller number of vehicle classifications results in some loss of precision (i.e., it is not possible to distinguish how travel patterns for two FHWA classes that fit within a single aggregated class differ), but results in a more stable set of adjustment factors. This results in a better estimation of loading patterns and therefore total loads. Many states maintain equipment that can classify vehicles by total length using two induction loops (for example, speed monitoring equipment). While total length does not provide a precise measure for differentiating vehicles by class, it does allow states to develop a reasonable picture of the volume of vehicles in the basic categories of passenger cars, small commercial trucks, single trailer trucks, and multi-trailer trucks. For many pavement analyses these categories are sufficient. Table 7.5 illustrates the bounds used for length categories used by Washington and Idaho.

Table 7.5 Washington and Idaho Vehicle Length Classifications

	State	Minimum Length	Maximum Length
Bin 1	Washington		<26 feet
	Idaho		<20 feet
Bin 2	Washington	26 feet	39 feet
	Idaho	20 feet	40 feet
Bin 3	Washington	39 feet	65 feet
	Idaho	40 feet	70 feet
Bin 4	Washington	65 feet	115 feet
	Idaho	40 feet	148 feet

Besides the loss of precision, the primary disadvantages of using the vehicle length classes are the facts that FHWA vehicle classification categories do not fit cleanly into vehicle length categories. Also, states tend to use different length classification boundaries; making it more difficult to compare travel patterns and trends between states (*4*).

The exceptions to this recommendation are high volume interstate and principal arterial routes, where sufficient volumes are present within each of the FHWA categories to calculate stable adjustment factors for all 13 FHWA classifications.

Combining Group Means To Obtain Statewide Estimates: The methodologies described above develop mean estimates of various attributes for each group of roads defined by an agency. An agency may be interested in determining the statewide mean damage factor per truck or mean damage factor for each truck type. Unless the state uses a single truck weight factor group for the entire state, this value must be obtained by combining the damage factors from each group. (If the state uses a single group of roads as its sample basis, that one group mean is the mean for the state.)

Where more than one group exists, two alternative approaches can be used to estimate the statewide average. The better of these two techniques weighs the mean damage factor from each group of roads by the proportion of statewide truck travel that occurs within that group. To compute this statewide mean, analysts must know the annual vehicle miles of travel for trucks within each group of roads; these estimates can be used to weight the damage factors from each group. This computation can be expressed as shown in Equation 7.5.

Equation 7.5:

$$SDF = \sum_{0}^{n} \left(\frac{DF_i * VMT_i}{\sum_{0}^{n} VMT_i} \right)$$

Where:

SDF =	the statewide mean damage factor,
VMT_i =	the VMT for that truck class in region i,
Df_i =	the damage factor for that truck class for region 1, and
n =	the number of regions in the state.

This approach assumes that all roads in a group have statistically similar damage factors and then weights the group means on the basis of their contribution to statewide travel. It is most accurately applied when truck VMT is known for individual classes of trucks so that the statewide mean damage factors can be computed separately for each truck class.

When VMT by factor group is not available, the second aggregation technique is to compute the average daily damage factor for each weigh station in the state. This is then calculated using a straight average of those values or the average of the damage factors by using a weighting factor equal to the proportion of average daily volume (by truck class) at each site divided by the total volume for that class for all sites combined.

The straight average assumes that the selected WIM sites are equally representative of statewide travel, regardless of volume. (That is, it assumes that the volume of trucks on a road is not a good estimate of how "representative" that site is of damage factors within the state.) The weighted average assumes that "a truck is a truck," regardless of where it is weighed

and that each truck weighed should be treated equally. Insufficient information is available to prove or disprove any of these assumptions.

7.14 Cost Estimate

The costs to establish a traffic file with this level of truck monitoring detail are substantial. The work by Mark Hallenbeck was based on traffic studies conducted in Florida and Washington. Washington State DOT has about 10,000 centerline kilometers of roadway in their highway system. Regarding size and highway use Washington State comes very close to representing the Average State with an equal number of States being larger and smaller than Washington State. In Washington State's Data Rationalization Study, the number of Weight Sites was estimated based on the risk of not having the necessary truck-loading estimate (ESALs) for pavement design. Considering the variability in truck load movement across the State highway network it was determined that the DOT should have approximately 21 truck weighing sites distributed across the full range of functional class highways. In addition, there were approximately 60 permanent automatic vehicle classification (AVC) sites already in place. The number of AVC was judged reasonable, but they needed to be better distributed across the full range of functional class highways.

The WIM system was put in place throughout out the highway system and additional AVCs were added to those functional classes where they were deficient. The WIM system consisted of 19 Piezo Cable and 3 Bending Plate units. The bending plate units were installed in Portland Cement Concrete Pavements on the Interstate Highways. The Piezo Cable Units were installed on the Principal and Secondary Highways

The total cost of installing this WIM System was approximately $1,000,000. The cost to operate and maintain this system is about $750,000 annually. This operational cost includes funding for a staff of 12 people to repair, calibrate, and maintain the system, as well as collecting and analyzing the data. It also includes the cost to replace WIM equipment as it fails, and to repair the pavement as needed to provide smooth approaches to the WIM scales. The system also included sensors for two lanes of traffic. The initial and annual costs could be reduced about 25% if only one lane was monitored.

The total cost for maintaining a permanent AVC system is in the same general range. The AVC system is less expensive and a lot more durable but there are about three times as many sites to operate and maintain. However, the permanent AVC system plus a fairly active portable AVC system is required to maintain the basic Agency Traffic File, so it is usually already in place in most State Highway Traffic Monitoring Systems.

The FHWA Traffic Monitoring Guide requires both the vehicles counting systems and the truck weighing systems. However, the current FHWA Traffic Monitoring Guide calls for a little less truck weighing than that indicated by the Truck Loads and Flows Study, however is in the process of being revised and the new Guide will undoubtedly provide more detailed guidance in line with the results of this study.

7.15 Summary

The information in this module has focused exclusively on how to obtain accurate traffic data. In particular, the difficulties and challenges in obtaining such data have been discussed. In most PMS, traffic data used in performance prediction models or as inventory data or for project level analysis, is obtained with little or no information on how it was generated. This module seeks to educate and inform the participant on the need for accurate data.

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MODULE 8

PERFORMANCE MODELS

8.1 Module Objectives

This module introduces the use of pavement performance models to predict future pavement conditions for the highway network as part of the agency's pavement management activities. The types of models normally used at the network and project level are introduced and examples of the principal approaches are provided. Guidelines on determining the reliability of the performance models and update requirements are also provided. Upon completion of this module, the participant will be able to accomplish the following:

- Understand the use of performance models in pavement management.
- Identify the common modeling approaches used to develop models for pavement management.
- Understand methods for evaluating the reliability of the pavement performance models.
- Describe the requirements for updating the models over time.

8.2 Overview of Performance Modeling

Transportation agencies responsible for the preservation of a highway network commit large portions of their budgets toward the collection of monitoring data that represent the current condition of its pavements. One of the primary motivations for this expenditure is to objectively identify historical performance trends so the information can be used in planning the maintenance and rehabilitation of the pavement network.

Traditionally, pavement performance has referred to the serviceability-performance concepts defined by Carey-Irick (*13*) which represent performance as the variation or history of pavement serviceability with time. Since that time, the term performance has been used loosely by individuals in the pavement management field. As a result, it has become common practice among practitioners and researchers to use terms such as deterioration to represent the change in pavement performance over time. For the purpose of this course, the term performance models will be used to represent the pavement deterioration patterns that are modeled.

Pavement performance models vary depending on the type of performance that is being modeled. For example, pavement condition can be defined in terms of measured quantities of distress or a subjective rating based on a visual assessment of the overall condition of a pavement section. Individual distress quantities may be used to drive maintenance and/or rehabilitation activities, or the information may be combined to calculate a condition index. Performance models could be developed for each individual distress mechanism or for the condition index, depending on the decision process within the agency.

A number of different modeling techniques can also be used depending on the use of models within the agency. For example, an agency may want to predict future pavement condition as a function of traffic levels (in terms of equivalent single axle loads (ESALs)) or pavement age. Another agency may require more complex models that predict pavement condition as a function of traffic levels, material properties, and climatic influences. This modeling approach would require significantly more detailed data than the previous example. The data requirement would directly impact the resource requirements for collecting and maintaining the data.

Uses of Performance Modeling in Pavement Management: Pavement management is dependent on the quality of the information contained in its database, which includes both inventory and monitoring information. The database alone, however, is of little use without mathematical expressions, or models, to predict future pavement condition. Pavement performance models are an important component of a multi-year analysis for the types of activities listed below.

- Estimating the type and timing of maintenance and/or rehabilitation as part of a multi-year improvement program.
- Predicting the length of time until a lower limit of acceptable pavement condition is reached (sometimes referred to as the remaining service life).
- Optimizing the combination of projects, treatments, and timing to achieve agency goals.
- Evaluating the long-term impacts of various program scenarios.
- Providing a *feedback loop* to the pavement design process.
- Estimating pavement life-cycle costs.

Performance models are used differently at the network and project levels within a pavement management system. At the network level, performance models are primarily used for the functions listed above. For these types of decisions, models are typically based on changes in performance measures such as roughness or distress from representative samples of the pavement network. As a result, these models should be considered estimates of the deterioration trends of the network. In addition to providing a summary of changes in performance measures for network-level analyses, the models can be used to summarize the impacts of different maintenance and rehabilitation strategies in terms of overall network condition, the percent of the network in various condition categories at some point in time, or some other representation.

Project-level models are generally more detailed than network-level models. These models are used in the analysis of specific pavement designs and in the life-cycle cost analysis of different design approaches.

The way a model will be used influences the selection of model type. The most common approaches used at the network level include deterministic and probabilistic models (Lytton 1987). The deterministic models include those used for predicting primary response, structural, function, and damage performance of pavements. The probabilistic models include survivor curves, Markov, and semi-Markov transition processes. In most instances, deterministic models use regression analysis to predict a single value of something (such as condition) from one or more variables (such as age or traffic). Probabilistic models, on the other hand, predict a range of values of something (such as condition). Probabilistic models are based on probability transition matrices that estimate the likelihood of pavement sections changing from one condition state to another.

The different uses of these models in transportation agencies have been summarized based on work by Lytton (*14*). Table 8.1 summarizes the principal types of models used by transportation agencies at different levels within the organizations.

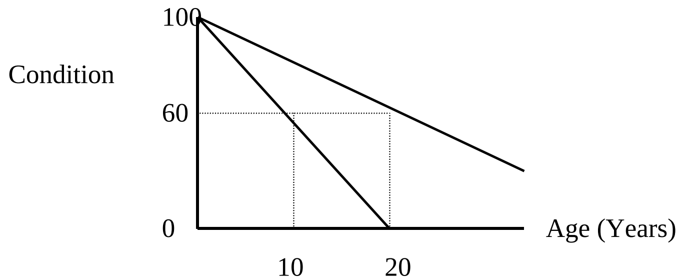
Table 8.1 Types of models used at different levels within a transportation agency.

	Types of Performance Models						
	Deterministic				Probabilistic		
	Primary Response	Structural	Functional	Damage	Survivor Curves	Transition Process Models	
	Deflection Stress Strain	Distress Pavement Condition	PSI Safety	Load Equiv.		Markov	Semi-Markov
National Level				✔	✔	✔	✔
State or District Level		✔	✔	✔	✔	✔	✔
Project Level	✔	✔	✔	✔			

As shown in the table, higher levels of management are more interested in the probabilistic models and other models that predict composite indexes of the pavement condition for the network. At the national level, performance models are used primarily for policy and economic matters, especially with respect to the allocation of funds. At the state, province, or district level, there is less concern about the performance of individual pavement sections and more of a focus on the overall condition of the pavement network for the entire state (or province) or a subset of the network (such as a district). These models are important for estimating current and future funding needs and identifying priorities among agency-wide maintenance and rehabilitation needs. At the project level, the focus is on the performance of particular pavement sections or design approaches. At this level, more detailed information is usually available for model development.

The Importance of Accurate Modeling in PMS: Because of the importance of performance models at the network- and project-level, the models must reflect the best possible representation of the pavement deterioration. The following example is provided to illustrate the effects of poor models on network-level decision-making. In this example, the agency normally triggers rehabilitation for pavement sections with an overall condition index of 60. The timing of rehabilitation for each pavement section is dependent on the accuracy of the performance model, as shown in Figure 8.1. In this instance, an inaccurate performance model could have a significant impact on the projects identified for the multi-year improvement program and the timing at which each project is recommended. It also impacts the life-cycle cost analysis results used in either a network- or project-level analysis.

Figure 8.1 Impact of performance models on multi-year analysis recommendations.



Obviously, this example was kept very simple to illustrate the importance of quality data in the development of performance models. The degree of accuracy required is a function of the intended use for the models. In general, network level models are less specific than project level models, so the accuracy of these models is expected to be less.

Each of these factors will be discussed in more detail later in this module.

8.3 Performance Model Development

As discussed in the previous section, the development of performance models is a critical component of a multi-year analysis within a pavement management system because all system recommendations and economic analyses are based on the projected condition levels. There are four basic criteria that should be followed to develop reliable performance models at any level within the transportation agency (*8*). These include the following items.

- An adequate database.
- The inclusion of all significant variables that affect performance.
- An adequate functional form of the model.
- The satisfaction of the statistical criteria concerning the precision of the model.

Further, the literature emphasizes the importance of understanding the principles behind each of the models so that the proper model type and form can be selected. It is important that the data needed to develop the model be available and continue to be updated as changes occur. Finally, it is imperative that the limitations of each model be understood so that after the models are developed, they not be used outside the range of their intended use.

This section of the module discusses the different approaches used in the development of performance models and the data requirements for each of the approaches. It also discusses significant factors that must be considered during the development of the models.

Approaches to Model Development: There are a number of different approaches by which performance models can be developed, as shown earlier in Table 8.1. These models are classified into two distinct categories: deterministic and probabilistic. Deterministic models predict a single number for the life of a pavement or its level of distress (or some other measure of condition). Deterministic models can be primary response, structural performance, functional performance, or damage models. Probabilistic models predict a distribution of events based on the likelihood of occurrence for each event. Probabilistic models include survivor curves, and Markov or semi-Markov process models.

For operational purposes, these models have been further defined as shown below (*13*).

- Purely mechanistic, based on some primary response (behavior) parameters such as stress, strain, or deflection.
- Mechanistic-empirical, where a response parameter is related to measured structural or functional deterioration, such as distress or roughness, through regression equations.
- Regression, where the dependent variable of observed or measured structural or functional deterioration is related to one or more independent variables like subgrade strength, axle load applications, pavement layer thicknesses and properties, environmental factors, and their interactions.
- Subjective, where experience is captured in a formalized or structured way, using transition process models, for example, to develop deterioration prediction models.

To date, no purely mechanistic performance models have been developed. This is because pure mechanistic approaches are only applicable to calculating pavement response in terms of mechanisms such as stress, strain, or deflection. These pavement responses are normally caused by forces created by traffic, climate, or a combination of the two. Pure mechanistic models for calculating stress and strain are not classified as performance prediction models; however, the calculated stress and strain attributes could be used as the input for an empirical prediction model.

A prediction model that is developed using regression with pavement response as the dependent variable is called a mechanistic-empirical model (*12*). These models incorporate elements of both the mechanistic models (based on fundamental principles of pavement behavior under load) and empirical models (based on the results of experiments or experience). An example of this type of model is provided for predicting asphalt pavement fatigue life (N) (*12*).

$$N = A * (1/e)^B$$

Where N = asphalt pavement fatigue life

A, B = coefficients

e = the strain produced by wheel loadings

In this example, the strain is calculated mechanistically and the coefficients are determined through a regression analysis.

Regression analysis is widely used by state highway agencies for performance model development. This approach is primarily used in agencies with an historical database available. The State of Washington has used regression to develop its performance models, as illustrated in the examples at the end of the module.

The last approach listed, using subjective experience, is another way of developing preliminary performance models in agencies where an historical database has not been established or where insufficient information is available for certain pavement designs. This approach can be used regardless of whether deterministic or probabilistic models are desired.

Data Requirements: Data requirements for performance models vary depending on the type of model being developed. At the most basic level, inventory and monitoring information are used to develop the models. Inventory data include any network information that do not change with time or traffic, such as geographic location or section length. Monitoring data are influenced by time and traffic and are most commonly used as the dependent variables in developing performance models. Examples of monitoring data include pavement condition, cracking quantities, average annual daily traffic (AADT) levels, and so on.

A summary of the types of data used for each of the predominant modeling approaches is presented in the literature (*2*). Table 8.2 was developed based on the earlier work of Lytton to summarize the use of inventory and monitoring information in model development. It should be noted that not all the data elements listed are required to develop models. In some cases, models can be developed with little more than pavement surface type and age data. However, the reliability of the models is generally improved when additional variables that influence pavement performance are considered.

Most agencies rely on historical databases comprised of field measurements and observations of each data type that have been collected for a number of years. There are some agencies that may not have established historical databases, or agencies that have modified their methods for monitoring pavement conditions, and do not have a sufficient amount of historical data available for model development. Agencies faced with this situation often wait until sufficient levels of data are available before developing models. As a result, they are not able to conduct a multi-year analysis. In recent years, a number of agencies have been able to develop preliminary models that can be used for a multi-year analysis based on input from experienced practitioners within the agency (*4,11,20*). These models, referred to as expert models, are based on the pavement performance observations made by experienced highway personnel involved in the design, construction, and maintenance of the agency's pavements. As an historical database is established, the expert models are supplemented with actual field data until a sufficient level of field data is available from which updated models can be developed.

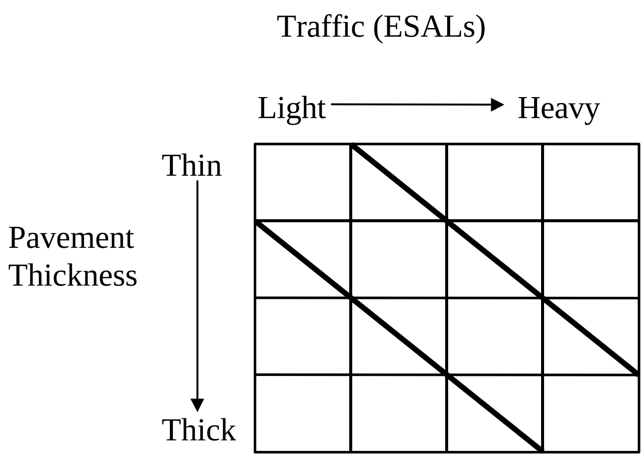
Table 8.2 Summary of data used to develop different types of performance models.

Data Requirements	Deterministic	Probabilistic (Markovian)
Inventory Data		
Pavement Structure	Required	Required
Joint Features	Useful	Useful
Drainage Characteristics	Useful	Useful
Age	Required	Required
Prior Condition/Traffic	Required	Required
Environmental/Climatic	Useful	Useful
Material Properties	Useful	Useful
Monitoring Data		
Distress	Required	Required
Traffic	Required (may be in traffic categories rather than exact counts)	Required (may be in traffic categories rather than exact counts)
Deflection	Useful, if available	Useful, if available
Profile	Useful, if available	Useful, if available
Maintenance History	Useful, if available	Not required
Condition Index	Required	Required

The specifications for the data requirements also vary depending on whether the models will be used at the network or project level. At the project level, very specific project information is often available, such as the condition history, the results of a distress survey, the age of the pavement, the length of time since the last rehabilitation action was applied, the pavement structure, and the traffic levels.

On a network level, the same types of specific information may not be available for model development. The network level models are further complicated by what is referred to as the *on-the-diagonal problem*, which is illustrated in Figure 8.2 (*14*). This issue arises from the attempt to model network-level pavement performance data for designed pavement structures. This phenomenon makes it difficult to observe differences in pavement performance at the network level due to factors such as traffic, material variances, and climatic conditions because most of these factors are accounted for in the design of the pavement structure through design programs. As a result, if an agency sought to model the effect of traffic on pavement performance, this is difficult to do without also looking at pavement thickness because the thickness is a related factor that is affected by the anticipated level of traffic. Without considering thickness data in the models, pavements with equal design periods would show little variation in condition with traffic alone.

Figure 8.2 ***On the Diagonal*** **performance issue that must be considered in the development of network-level models (*14*).**

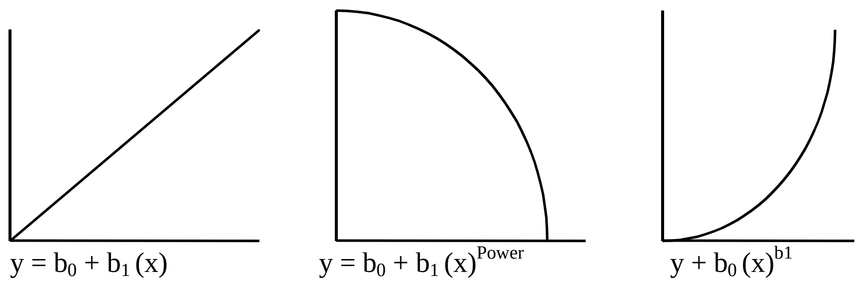


Significant Factors in Model Development: It has previously been emphasized that pavement performance models are a critically important component of a pavement management system so that a multi-year analysis can be conducted and future conditions considered. This module has already discussed the basic criteria to use in developing models: an adequate database, the inclusion of all variables that significantly impact pavement performance, an adequate functional form, and a model that meets the proper statistical criteria for precision and accuracy (*8*). There are other factors that must be accounted for in the development of pavement performance models (*2*). These factors include the following items.

- An understanding of the principles underlying each type of model.
- The selection of the appropriate model form.
- The role of statistics and mechanics in developing an appropriate model.
- The identification of the data needed for a specific model.
- The modification of the models to represent the effects of maintenance.
- The limitations and uses of the different types of models.

The principles underlying each of the main types of performance models are discussed in the next sections of this module along with guidance on the selection of an appropriate model form. The functional form of the model, or the way in which the variables are arranged, can only be determined through consideration of the actual relationships between the variables and the trends from the data on plots. Several examples of deterministic model forms are illustrated in Figure 8.3. The selection of the appropriate model form can not be left to the computer. Rather, it is important that the individual developing the model understand the relationships between the variables being considered.

Figure 8.3 Deterministic model forms.



Statistics plays an important role in assessing the precision of a pavement performance model. As discussed previously, the individual developing the model must use judgment to determine the form of the model being developed. The data are then plotted and examined to verify or modify the initial selection. Statistics should not be used to select a model form unless all forms being considered adhere to the boundary conditions and other physical principles that govern the variable being modeled. Statistics do play an important role in evaluating the following items.

- The overall test for goodness of fit of the model.
- A test for the specific coefficients used in the model.

Statistical tests used to evaluate either of these factors, such as the coefficient of determination (R^2), can only test the precision of the data used to develop the model. Remember, both good and bad quality data may result in a good statistical fit for the model. If the data do not represent the actual conditions in the field, a model with high levels of precision will not accurately model future performance.

The issue of data was discussed previously. In order to develop reliable performance models it is important that a sufficient amount of data be included in the model development and that the data be measured accurately and without bias. The data must be representative of the pavements for which the model is being developed. It is also important that the data be maintained over time so that the models continue to reflect the actual pavement performance trends. For that reason, the amount of the data must be considered from a practical point of view to ensure that the agency can collect and maintain the data within any cost and time constraints.

Finally, it is important that the models be used appropriately, so the limitations of each model must be considered. This relates directly to the selection of the appropriate form of the equation so that all physical and mathematical boundary conditions are satisfied.

8.4 Deterministic Performance Models

Deterministic models are one of the most common types of models used for a multi-year pavement management analysis. Deterministic models predict a single number based on its relationship with one or more variables. These models may be either empirical (based on data from in-service pavements or from full-scale tests) or mechanistic-empirical (usually mechanistic models that use empirical field data) correlations that are calibrated using regression techniques that statistically develop relationships between two or more variables. In a pavement performance model, some type of condition (such as an overall condition index or distress quantity) is modeled as a function of variables such as pavement age, traffic, environment, pavement construction characteristics, and maintenance and rehabilitation actions.

REGRESSION ANALYSIS: Regression analysis is a statistical tool used to establish the relationship between two or more variables. Models developed through a regression analysis can be either linear or non-linear, depending on whether or not the relationship among the variables can be defined in terms of a straight line. Regression is one of the most widely used and powerful analysis techniques available for constructing pavement performance models.

The simplest model form is linear regression between two variables. In a linear regression, the relationship is expressed in terms of the following equation.

$$Y = a + bX$$

where Y = the dependent variable
X = the independent variable
a, b - regression parameters

If more than one variable is used to predict the dependent variable (Y), the equation takes the form shown in the next equation. This type of linear regression analysis is known as multiple linear regression.

$$Y = a_0 + a_1X_1 + a_2X_2 + \ldots a_nX_n$$

A nonlinear regression is used when the relationship between the dependent and independent variables is not linear. In these instances, polynomial regression is used frequently, resulting in a model that has the form shown below.

$$Y = a_0 + a_1X + a_2X^2 + \ldots a_nX^n$$

In polynomial regression, the number of curves in the regression line is equal to one less than the degree of the polynomial. In some cases, polynomial regression equations are constrained so that the curve can not increase over time. The common S-shaped deterioration curve is a result of a polynomial regression.

The relationships between the independent and dependent variables are rarely exact. The best equations to use to predict the value of Y from some value of X is one that minimizes the differences between the regression line (or curve) and the actual data (*14*). The term *least squares fit* comes from the minimization of the squared differences between the actual data points and their corresponding points on the fitted line (or curve). Polynomial least squares models are a popular approach for predicting the change in the dependent variable as a function of the independent variable(s).

To judge how well an equation fits the actual data, there are a number of parameters that can be used. These include the coefficient of determination (R^2) which explains how much of the total variation in the data is explained by the regression equation (or curve) and the root mean square error (RMSE) which is the standard deviation of the predicted Y values for a specific value of X. Hypothesis tests on regression constants which are generally based on the t-statistic are also used.

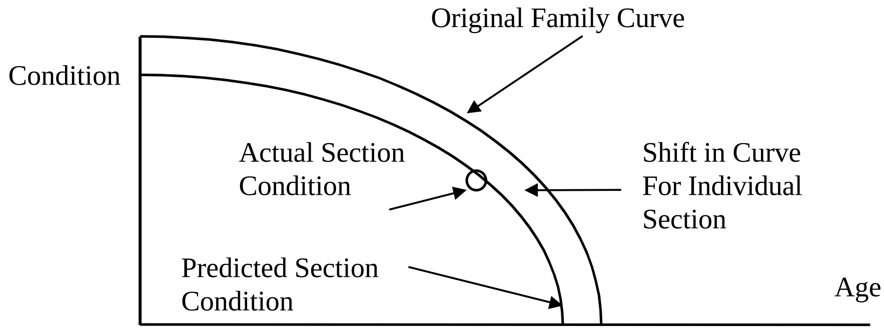
Family Models: Because of the large number of variables that can be involved in a regression analysis, techniques have been developed to simplify the process (*22,19*). These techniques involve grouping pavements into *families* that have common characteristics such as surface type, functional classification, traffic levels, and geographic location. This approach is based on the assumption that each pavement section within a family has a similar deterioration pattern. The pavement performance model developed for the family represents the average deterioration pattern for all sections included in that family.

When families of pavement sections with similar characteristics are developed, the regression analysis need only analyze pavement condition in terms of age, greatly reducing the number of variables in the regression equation. The use of variables such as pavement type, traffic, and pavement use is roughly equivalent to including three additional variables into the development of the model (*19*). An additional variable, climate, is implicitly included if pavement families are also defined based on individual geographic locations.

The family approach has been used successfully by agencies with databases that do not have the type of data necessary for more involved model development, or can not collect some types of data on a regular interval as needed to support more sophisticated models over time. For example, agencies that do not have exact traffic counts for their roadways would find it difficult to include equivalent single axle loads (ESALs) as one variable in the regression analysis. By using family classifications, pavements with similar ESAL characteristics, without knowing exact traffic numbers, can be grouped together for performance modeling purposes.

Since the family performance model is representative of the average deterioration pattern of all the sections in the family, the deterioration pattern of each individual section can be expected to vary slightly. Typically, the predicted performance of each section is defined in terms of the section's position relative to the family prediction curve. In these cases, it is assumed that the deterioration of all the pavement sections in a family is similar and is a function of only present condition, regardless of age (*12*). As a result, the condition of an individual section is determined by shifting the family curve to intersect the condition point for the section. This shift is always kept parallel to the family prediction curve, as shown in Figure 8.4.

Figure 8.4 **This figure illustrates the shifting of a family performance model for predicting the condition of an individual section.**



Advantages/Disadvantages: Deterministic models using regression analysis are common in agencies seeking network-level models for a multi-year pavement management analysis such as multi-year prioritization. These models are popular because they are fairly easy to develop and interpret and can be developed with commonly available statistical analysis packages. Deterministic models can also be developed with any number of variables and a number of different model forms. The family modeling approach provides a way for regression to be used for model development without the direct use of certain variables in the model equation.

There are also limitations that must be understood in the use of deterministic models developed through regression analysis. In general, these models do not explicitly deal with errors in the data or the functional form of the model. In addition, it can be difficult to measure many of the relevant independent variables, such as construction quality or maintenance effort (*7*).

8.5 Probabilistic Performance Models

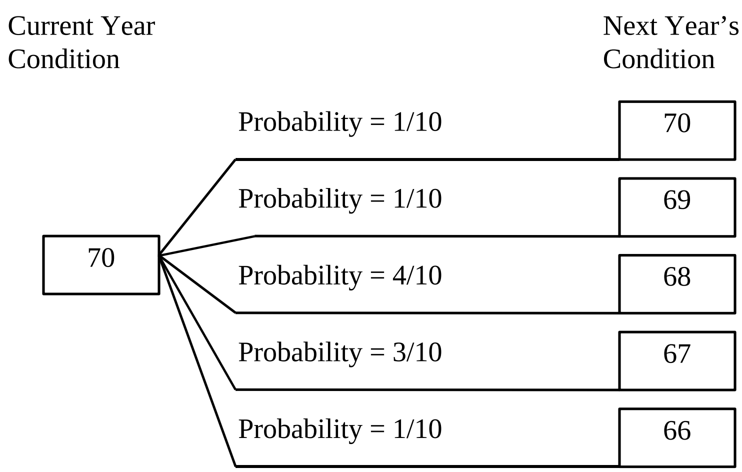
Another common approach used to develop pavement performance models is the use of probabilistic models that predict a range of condition values rather than a single value of condition. Probabilistic models include survivor curves and Markov process models. Survivor curves represent the percentage of pavements that remain in service as a function of time (*7*). They are useful for determining the service lives of various maintenance and rehabilitation activities at the network level. Markovian theory is founded on the assumption that the probability that a pavement will change from one condition state to another is only dependent on its current state. In a pavement management application, this assumption means that a pavement segment's current condition is only dependent on its preceding prior condition and that the next year condition of a pavement segment is only dependent on its current year condition. Markov-based models are frequently used as a means of incorporating uncertainty into the prediction of future pavement condition for pavement management analyses.

Markov Process Models: Markov process models are developed from estimates of the probability that that pavements in a given condition state will either stay in the same condition state or move to another condition state. The probability of each of these events is estimated based on historical field data or the experience of agency personnel. This concept is illustrated in Figure 8.5 (*from Ref. 2*).

As shown in Figure 8.5, there is a 1 in 10 probability that the condition of a pavement section with a condition rating of 70 will be either 70, 69, or 66 in the next year. Similarly, there is a 3 in 10 chance that the condition rating will be 67 and a 4 in 10 chance that the condition rating will be 68. The probabilities of each event are referred to as transition probabilities which represent the likelihood of a pavement section transitioning from one condition state to another. The Markov assumption implies that the next year's condition is independent of how the pavement acquired the current

2).

Figure 8.5 **The probability of change in the condition of a pavement section.**



In order to develop Markov models, condition states must be defined for each pavement category (similar to a pavement family). The technique is based on determining the probabilities associated with pavements in a given condition state, by either starting in that state or deteriorating to the next state after one cycle. A cycle may be a 1-year period, or any other length of time, and is representative of a fixed period of climatic effects or traffic loadings or some other similar measure.

The condition states and the transition probabilities between states are defined in a probability transition matrix, such as the one shown in Figure 8.6. In this example, taken from the Washington State Department of Transportation's work in the early 1970s, the probability states are based on two-year intervals. The matrix shows, for example, that when a pavement is in condition state 9 (a condition rating of 90 to 100), there is a 90 percent chance that it will remain in condition state 9 after two years and a 10 percent chance that it will move down to a condition state of 8 (condition rating of 80 to 90). There is a zero percent chance that the condition rating will be in any other condition state. Although not shown in this example, there can be some states known as holding or trapped states (*12*). Pavements in these states can not transition from these states unless some type of repair action is performed.

The Markovian process assumes that the transition process is stationary. In other words, the probability of changing from one condition state to another is independent of time. This assumption is not likely to be accepted for pavement performance because it implies that changes in climate or traffic do not affect the transition probabilities (i.e., the rate of deterioration). A technique which nearly eliminates this problem has been introduced by incorporating the use of zones representing different periods of time (*21*). With this technique, the zones each represent an increment of time over which the transition process is stationary. This is called a semi-Markov process. It is more realistic for pavement management purposes due to the fact that it accommodates changes in climate and traffic conditions that affect the transition process.

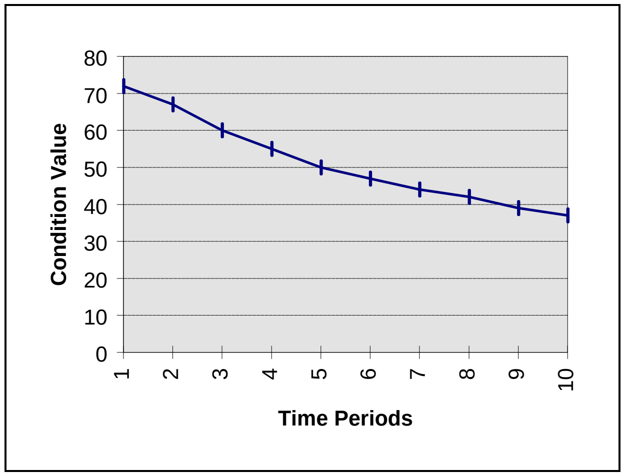
Figure 8.6 **This figure illustrates a Probability Transition Matrix from Washington (*14*).**

From Condition State
To Condition State

	9 100-90	8 89-80	7 79-70	6 69-60	5 59-50	4 49-40	3 39-30	2 29-20	1 19-10
9 100-90	0.9	0.1							
8 89-80	0.05	0.65	0.3						
7 79-70		0.05	0.6	0.25	0.1				
6 69-60			0.05	0.45	0.25	0.2	0.05		
5 59-50				0.05	0.25	0.4	0.3		
4 49-40					0.05	0.2	0.75		
3 39-30						0.05	0.65	0.3	
2 29-20							0.1	0.8	0.1
1 19-10								0.05	0.95

Using the probability transition matrices, an agency can develop pavement performance models (*14*). The calculation of the plotted points are based on matrix multiplication, the specifics of which are not covered in these notes. However, pavement conditions can be predicted at any point in the future as long as the initial condition state for a specific pavement and one step in the transition matrix are known. An example of a performance model developed using the probability transition matrix shown in Figure 8.6 is shown in Figure 8.7.

Figure 8.7 **Performance model developed from a probability transition matrix (*6*).**



Other Probabilistic Models: Another probabilistic approach, named after Thomas Bayes, is known as Bayesian statistic decision theory. Bayesian theory allows for both subjective and objective data to be combined in order to develop predictive equations using regression analysis. An example of this approach was provided in National Cooperative Highway Research Program (NCHRP) Project 9-4 (*14*). In this project, models were developed to relate pavement performance in terms of fatigue life to various pavement designer-controller variables, such as asphalt consistency (penetration), asphalt content (percent asphalt by weight of mix), asphaltic concrete proportion (percent thickness of the pavement materials above the subgrade consisting of asphalt concrete), and base course density (relative compaction based on AASHTO T-180). By using both the subjective opinions of experienced personnel and objective data obtained from mechanistic models, equations were developed. In a traditional regression analysis, the regression coefficients would have been assumed to have a unique value. Using Bayesian regression analysis, the regression parameters were found to be random variables with associated probability distributions.

Advantages/Disadvantages: Probabilistic performance models have been successfully used by a number of agencies as a means of incorporating uncertainty into the prediction of future pavement condition. There are several advantages to probabilistic approaches, such as the Markov process model. One advantage is that the experience of agency personnel is incorporated into the model development through the construction of probability transition matrices. Another advantage is that models can be developed without an historical database, relying entirely on agency experience. Techniques have been developed for calibrating expert models with field data as an historical database is developed (*23*). These models are relatively simple to implement and they provide a network-level assessment of facility condition.

The following list summarizes the major advantages associated with probabilistic modeling approaches (*14*).

- It provides a convenient way to incorporate field data into a prediction model.
- It lends itself to subjective inputs of experienced agency personnel.
- It provides a mathematical means for obtaining performance predictions.
- It provides a probabilistic distribution of the expected condition value with time which will be required to identify those sections performing significantly differently than would be expected.
- It reflects performance trends obtained from field observations regardless of non-linear trends with time.

There are also several disadvantages associated with probabilistic approaches. Perhaps the largest disadvantage is the need to develop a transition probability matrix for each combination of factors that affect pavement performance. In some agencies, this can require a large number of matrices be developed. It is also difficult to incorporate pavement history into the model development since the estimate of future condition state is based only on the current condition state. The Arizona DOT uses rate of crack change as one of the condition state factors, thereby allowing pavements with a rapid deterioration history to have a greater probability of a pavement transitioning to a lesser condition state than pavements that do not have a history of rapid crack development (*13*).

The following list summarizes the major disadvantages associated with probabilistic modeling approaches (*14*). The list emphasizes the importance of validating the basic assumptions for using these models.

- It does not provide any guidance as to the physical factors which contribute to the change in condition.
- It is time independent so the probability of changing from one condition state to a lower condition state is not influenced by the age of the pavement and the probabilities are constant over time.
- It assumes that the transition from one condition state to another is dependent only on the present condition state without necessarily considering other factors that influence the deterioration rate of a pavement.

8.6 Expert Models

Expert models allow an agency to develop pavement performance models without the advantage of large, historical databases. Expert modeling techniques can be used by agencies just beginning their pavement management activities, or by agencies that wish to develop performance models for new rehabilitation activities (for which no historical data exist) or that incorporate the use of a new condition rating technique. Other instances when expert opinions may be used include the need to override the effects of maintenance (to represent do nothing conditions) or to establish a terminal serviceability and life span for the performance model (*11*). Expert opinions may be used to develop an entirely new model or to supplement a model developed through other means, especially where gaps occur in the historical database.

The techniques used to elicit expert opinions vary depending on whether a deterministic or probabilistic model is to be developed. For the development of deterministic performance models, the emphasis is on the expected pavement deterioration over time. Expert opinion has been used to estimate the condition of pavements at various points in time, including an estimate of the length of time until a threshold condition has been reached. Some agencies have found it easiest to plot representative performance curves and then verify the plots using existing pavement sections at various ages. Although these approaches are relatively simple to implement, they often fail to recognize the different shapes of performance curves that may exist for different conditions.

If probabilistic performance models are being developed, both the expected behavior and the likelihood of certain behaviors must be assessed. Several approaches may be used to estimate probabilistic models. These include sketching the performance curves with a band of uncertainty around them, estimating the probabilities of going to different pavement conditions following various rehabilitation actions, and estimating the probability distributions of the rate of pavement deterioration (*16*).

As field data become available, expert models can be improved by combining the subjective opinions with the newly acquired field data. Formal approaches to this activity are referred to in the literature (*16*). These approaches consist of weighting the subjective probabilities and the statistical parameters that are obtained from objective data by the number of data points. By taking into account the degree of uncertainty selected in subjective assessments, an equivalent data sample size can be developed for probabilistic approaches. This technique allows an agency to place more and more weight on the objective data as they are collected and less weight on the subjective estimates. Over time, the updated estimates will match the models obtained directly from field data.

There are a number of ways to ensure that expert models are representative of network conditions and not simply the opinion of one individual. One way is to form a team of experts from within the agency to develop the models. These individuals may represent different interests within the agency, such as maintenance, design, and research. Even if total agreement is not reached by the committee, the process will allow various viewpoints to be considered, thereby improving the reliability of the results. Another approach is to make independent checks of the models by asking questions about pavement performance in different ways to verify that the responses do not vary significantly from the expert models.

8.7 Reliability of Performance Models

Because of the importance of pavement performance models within a highway agency, it is imperative that the models reliably predict future performance. The level of reliability needed is influenced by the way in which the model will be used and can be evaluated through the use of statistical tools. These topics are further discussed in the following sections.

Differences in Network and Project Model Reliability: The use of a pavement performance model in pavement management activities has a significant influence on the expectations of the model in terms of reliability. In other words, an agency's expectations for how well the model predicts future pavement performance is very much a function of whether the model is developed at a project or network level.

In general, network models often require transformations of the independent variables in order to adequately predict the dependent variable. These transformations, which may include logs, natural logs, or square roots, are often selected only through a process of trial and error. As discussed earlier, at the network level an agency must also be concerned with the correlation between independent variables (as discussed in an earlier section with an example of the relationship between pavement thickness and traffic levels). The correlation between independent variables serves to diminish the predictive capability of the model.

At the network level, deterministic models must also consider the significance of each of the regression coefficients. If a regression coefficient is found to be insignificant (a statistical way of saying the regression coefficient is close to 0), then the independent variable has little or no predictive capability for the dependent variable. Insignificant variables should be dropped from the equations or transformed in some way and evaluated again for significance. Similarly, if multiple independent variables are considered, only the independent variables that substantially contribute to the overall predictive capability of the model should be included. Some variables that may be poor predictors of the independent variable will increase the coefficient of determination (R^2), but very little.

Table 8.3 summarizes the expectations of regression parameters as a function of the use of the model at the network and project levels. As is seen in the table, it is expected for project-level models to have a higher coefficient of determination (R^2), but lower root mean square error (RMSE). The coefficient of determination explains how much of the total variation is explained by the regression equation and the RMSE explains the standard deviation of the predicted values for specific values of a particular variable.

Table 8.3 **This table illustrates regression parameter expectations at the network and project level (*14*).**

Regression Parameter Expectations				
PMS Analysis Level	R^2	RMSE	Sample Size	Number of Independent Variables
Network Level	Medium to Low Values	Medium to High Values	Large Sample	More Than One
Project Level	High Value	Low Value	Small Sample	One

STATISTICAL EVALUATION OF MODELS: There are a number of statistical tools that are available for evaluating the fit of the performance models to the data from which they were developed. A detailed description of these tests is not provided here; however, a more detailed explanation of a statistical evaluation is provided elsewhere (*6*).

Prior to performing a statistical evaluation of the performance models, the agency must ensure that the form of its models adheres to the boundary conditions or other physical principles that influence the predicted value of the dependent variable. Statistical measures of fit should only be used to select the most appropriate model if there are a number of equations that meet all of the conditions.

In general the following parameters are evaluated to judge how well an equation fits the actual data.

- Coefficient of determination (R^2)
- Root mean square error (RMSE)
- Number of data points (n)
- Hypothesis tests on regression constants

The first test, the coefficient of determination, or R^2, provides an indication of how much of the total variation in the data is explained by the regression equation or performance curve. Network level models will often have R^2 values of less than 0.9 (sometimes much lower) while R^2 values for project level models are generally higher than 0.9.

The RMSE is the standard deviation of the predicted dependent variable value for a specific value of the independent variable. At the network level, RMSE values are typically higher than at the project level where RMSE values could be 5 or less.

The number of data points also influences the reliability of the resultant models. In general, the more data points used to develop a regression equation, the better. The last test, the hypothesis test of regression constants is generally based on the t-statistic. These tests are important for determining the significance of each regression coefficient.

It should be emphasized once again, however, that a statistical evaluation of performance models can only provide an estimate of the model's ability to represent the deterioration patterns of the specific data that were used in the development of the model. If poor quality data are used, or the data are not representative of actual conditions, the models may be statistically valid but not at all representative of the actual deterioration patterns of the agency's network.

8.8 Update Requirements

The importance of reliable pavement performance models has been discussed previously. Performance models are critically important in pavement management analyses because the basis of every recommendation relies on the predicted performance of the pavement sections in the agency's network. In reality, the impact of poor models is dependent to some extent on the current condition level of the pavement segment in question. For example, the predicted condition for pavement sections in poor condition will continue to be a low number that is undoubtedly recommended for rehabilitation action. On the other hand, a pavement section that is in good condition could be recommended for rehabilitation too early or too late, depending on the reliability of the performance model being used. Therefore, it is imperative that the reliability of the performance models be reviewed periodically, especially in the middle prediction ranges.

The development of pavement performance models should be a continuing task aimed at continual improvement in the models and better use of the data available. Over time, as new techniques and maintenance practices are developed, the performance models must be updated to reflect these changes.

It is also important that a feedback loop be established to link the deterioration models and the engineering practices within the agency. The models can provide important information concerning the effectiveness of one design strategy over another, the benefit of maintenance on overall network condition, or the actual performance of rehabilitation strategies considered in the pavement management analysis. The feedback loop provides each agency with a complete link between pavement management and engineering analysis.

8.9 Examples

A number of examples of pavement performance models are provided to better illustrate the concepts discussed in this module. Examples of both deterministic and probabilistic models are provided. The examples of deterministic models are taken from Washington and Illinois Departments of Transportation (DOT). The probabilistic model example is taken from the Kansas DOT.

Washington State Deterministic Model: The Washington State DOT (WSDOT) uses a pavement management program referred to as the Washington State Pavement Management System (WSPMS). The WSPMS developed out of an earlier priority programming process mandated by the Washington State Legislature. To satisfy the requirement, a priority programming process was developed based on the results of a system wide pavement condition survey. The system has evolved through an in-house process and in 1988 became operational on personal computers and an in-house local area network. The development of the performance models used in WSPMS is documented here, largely extracted from previously published material (*6*).

The development of performance models in the WSDOT system arose from its objective to achieve a predictive capability - something WSDOT felt could only be accomplished with a combined rating. The combined rating provided the Department with the ability to rank project needs and provide a pavement management condition rating versus age relationship so that time to failure might be predicted.

With this approach, raw coded data indicating severity and extent of each distress type are maintained in a Multi-year Survey File. These data are then translated into a combined rating in the interpreting phase, giving this system flexibility and the utility of an analytical tool. By utilizing parameters that are not an integral part of the interpreting program, distress weightings can be altered or adjusted after inspection of an initial run. This is an asset in calibrating weighting values for the types of distress rated, or studying any combination of distress types since weighting values can be zeroed for no influence.

An additional aspect of the interpreting phase is the potential for statistical analysis of performance trends. Since the interpreting program generates a file of performance data related to project segments, the results can be analyzed with statistical software packages. Topics of particular interest might include correlation of pavement performance to specific measures of construction quality, geographic location, pavement type, rehabilitation type, or even a specific version of construction specifications. Another feature of the interpreting function is to produce a performance curve that best represents a specific pavement's anticipated performance. Further, the performance curve can be used to predict future performance for the pavement section.

The general shape of the WSPMS performance curve is shown in Figure 8.8. As can be seen, as a pavement deteriorates with age the rate of deterioration increases each year until a state of slower deterioration is reached. This decelerated rate of deterioration can be attributed to the application of temporary fixes to hold the pavement together until a major remedy can be applied. These temporary fixes tend to cause short duration, random fluctuations in the pavement rating - probably best represented by a curve that passes through the mean value in this phase. The performance model developed for use in the interpreting program presently ignores the maintenance or temporary fix influence because it is assumed that WSDOT will initiate action prior to reaching the lower portion of the curves. A contemplated improvement in the future is to enhance the performance model by incorporating better representation in the lower range.

Figure 8.8 **Typical WSDOT performance curve.**

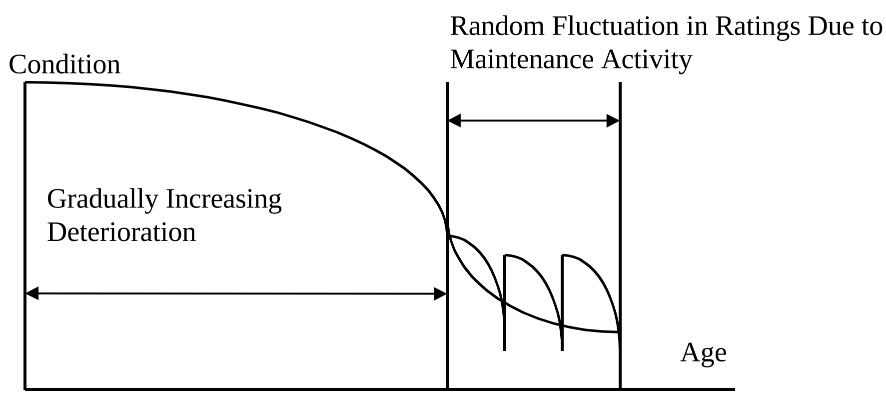
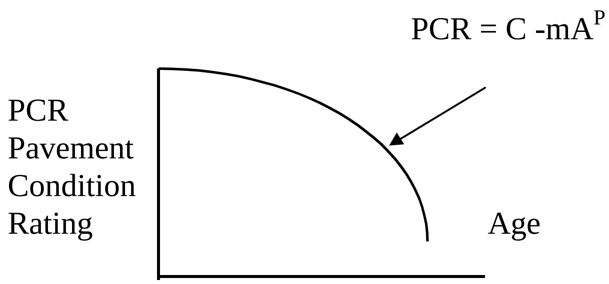


Figure 8.9 illustrates the general shape of the performance model used by the WSPMS to relate pavement condition to age. The general form of the performance equation is shown below.

$$PCR = C - mA^P$$

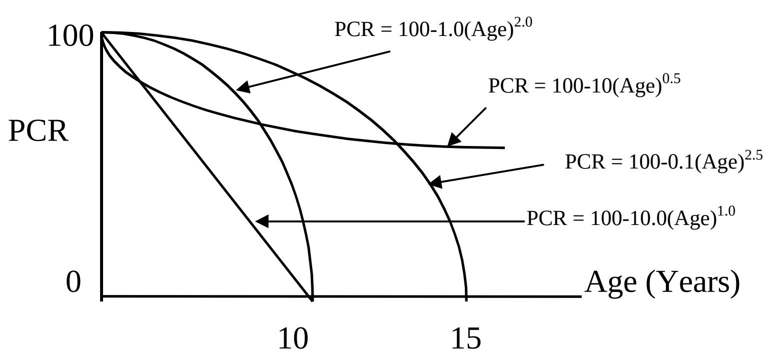
Where PCR and A represent pavement condition rating and age, respectively
C = the model constant for a maximum rating (approximately 100)
m = the slope coefficient, and
P = the selected constant that controls the degree of curvature of the performance curve.

Figure 8.9 WSPMS performance curve model.



As would be expected, different values of P influence the degree of curvature in the model. In general, values of P greater than 1.0 indicate convex curvature, while exponents less than 1.0 indicated concave curvature. Several examples of curve shapes are displayed in Figure 8.10.

Figure 8.10 Examples of WSPMS performance model curve shapes.



In fitting the best curve to the pavement ratings, the program substitutes a number of different exponents (P) to transform the independent variable, age. The best fit is determined by the highest R^2 value (coefficient of determination) and lowest RMSE (root mean square error) using the least sum of squares method.

Regression analysis is the initial approach employed in generating a performance equation for a specific pavement section. As one might expect, such analyses may not always produce acceptable performance equations for reasons such as the following.

- The project being analyzed may have a relatively new surfacing (or new structure), thus limiting the number of PCR versus Age points by which to develop a performance equation.
- Random fluctuation of condition ratings for some projects result in low R^2 values and high RMSE values (hence a poor fit of the data).

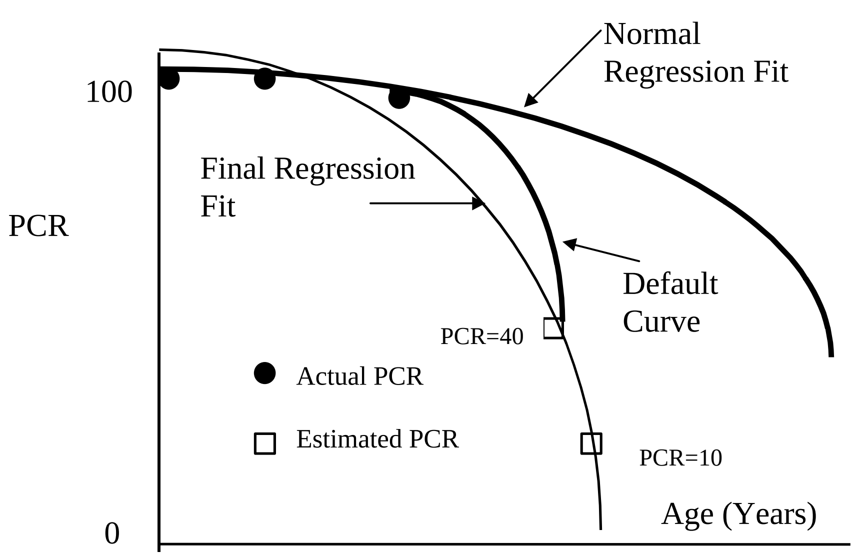
In the original interpreting program there were two basic automated methods of developing performance equations.

- In the case of a relatively new project where there has been no more than one rating since the last action or construction work, a standard, or default, equation for the pavement type, surfacing depth, and geographical area representing the average performance is used.
- Regression analysis is used for all the remaining projects that have at least three condition ratings (the beginning condition after construction and two visual ratings).

The standard regression curve building program required detailed hand editing of all project specific performance curves by PMS engineers with extensive experience in the design and construction of Washington State's pavements. For the 1986 model building year, 22 percent of the project performance curves were developed using standard (default) equations, 43 percent were developed using section specific data and regression analysis, and the remainder, 35 percent, were developed or adjusted using engineering judgment.

Though the WSPMS was developed around the concept of letting the individuals project "speak for itself" by developing performance (regression) curves for each project, this process overestimates remaining life in the early states of pavement deterioration. To better predict the most likely performance trends for each project, a third process was established that simply added the standard (default) curve to the last data point. The default curves are used to establish two artificial points that are added to the existing data points, then a regression equation is developed that best fits both actual and artificial data points. This process provides a more realistic estimate of specific project performance by recognizing the past performance trends unique to each project and also incorporating knowledge of the most likely rate of future deterioration from typical pavement performance experience. This process is illustrated in Figure 8.11.

Figure 8.11 Process used to prevent overestimation of pavement performance.



The third curve building process has almost totally eliminated the large amount of engineering edit required in the earlier system. Though there is a detailed engineering review of all curves before publishing the biennial program, very few changes are made in the program the automated system develops. As of 1990, over half of the curves were developed using this third curve building process.

ILLINOIS DOT DETERMINISTIC MODEL (*10*):

The Illinois Department of Transportation (IDOT) has been conducting a manual Condition Rating Survey (CRS) since 1974. As part of the CRS procedures, a panel made up of 3 to 5 technical persons from each of the nine districts has driven over the State's highways assigning a subjective value of 1 to 9 to represent the surface condition of the pavement, with 9 representing a pavement in excellent condition. In addition to the CRS rating, the type, severity, and extent of the 5 predominant distresses in each section are identified.

The CRS ratings are important to the Department for making policy decisions regarding pavement rehabilitation activities, and for assessing overall network condition throughout the state. In addition, the CRS is an important factor in the prioritization and justification of budgetary needs. Over the 20 year period in which CRS ratings have been collected, IDOT has gained a tremendous amount of confidence in the repeatability and applicability of the rating values. Two concerns within IDOT prompted the Department to investigate the feasibility of automating the collection of pavement condition data, as described below.

- Safety of the expert panel. A hazardous situation was created in the field by the slower moving vehicles carrying the expert panel. This situation was intensified by the panel parking the car on the shoulders of the road for closer inspection of pavement distresses.
- Reduction in staff and hiring restrictions. The expert panel methodology is labor intensive for senior members of the Department. Through an early retirement incentive, many expert panel members were no longer with the Department and hiring policies were essentially "to

As a result, IDOT purchased automated inspection vehicles for conducting its condition surveys and used this opportunity to develop models that could be used to calculate the CRS from automated measurements from the vehicle and the five predominant distress. The CRS calculation models were designed to produce CRS ratings that were consistent with the historical CRS values obtained without distress, rutting, and profile measurements. The resulting models were desired to meet the following specifications:

- Minimize the amount of time IDOT employees spent at the workstations developing a CRS value, and
- Develop a CRS rating that was $\pm$ 0.5 points from the historical value.

In addition to the development of models to determine a CRS rating from videotape, IDOT initiated the development of CRS prediction models that would forecast the future condition of the State's pavement network for planning and programming purposes. Specifically, the Department hoped to be able to perform the following types of activities with the performance models.

- Describe the expected pavement condition of the state highway system at given times in the future.

- Develop alternative pavement rehabilitation strategies, ranging from immediate action programs to long-term reconstruction, to keep the state highway system at various condition levels.
- Prioritize needed pavement improvements and scheduling of specific projects for preparation of the Department's multi-year highway improvement plan.

A number of different approaches were considered in the development of the pavement performance models, including both deterministic and probabilistic approaches. Due to the types of data that were available for model development, it was originally thought that developing models based on groupings of pavements with like characteristics, referred to as families, would be the most suitable approach. Data processing was performed on the data sets provided to improve the reliability of the resultant models and families were identified. Families were developed for the Interstate, non-Interstate, and Surface Maintenance at the Right Time (SMART) sections. Each of these groupings were further subdivided based on surface type, geographic region (Districts), and functional class. Any families that had little or no data available for model development were combined with other family groupings, resulting in the final families shown in Table 8.4.

Table 8.4 IDOT performance model families. (AC = asphalt concrete pavements, JPC = jointed plain concrete pavements, JRC = jointed reinforced concrete pavements, CRC = continuously reinforced concrete pavements, and PCC = concrete pavements)

System	Model
Interstate	AC/JRC districts 1 4
Interstate	AC/JRC districts 5 9
Interstate	AC/CRC districts 1 4
Interstate	AC/CRC districts 5 9
Interstate	JRC districts 1 4
Interstate	JRC districts 5 9
Interstate	CRC districts 1 4
Interstate	CRC districts 5 9
Non-interstate	AC surface treatments districts 1 9
Non-interstate	Flexible pavements districts 1 4
Non-interstate	Flexible pavements districts 5 9
Non-interstate	AC/PCC districts 1 4
Non-interstate	AC/PCC districts 5 9
Non-interstate	AC/JPC districts 1 4
Non-interstate	AC/JPC districts 5 9
Non-interstate	AC/JRC districts 1 4
Non-interstate	AC/JRC districts 5 9

Table 8.4 Continued

	Model
Non-interstate	AC/CRC districts 1 9
Non-interstate	AC/Brick districts 1 4
Non-interstate	AC/Brick districts 5 9
Non-interstate	PCC districts 1 4
Non-interstate	PCC districts 5 9
Non-interstate	JPC districts 1 4
Non-interstate	JPC districts 5 9
Non-interstate	JRC districts 1 4
Non-interstate	JRC districts 5 9
Non-interstate	CRC districts 1 4
Non-interstate	CRC districts 5 9
SMART	Flexible pavements
SMART	AC/PCC
SMART	AC/JPC
SMART	AC/JRC

Initially, models were developed using a constrained, fourth degree polynomial curve fit to the age versus condition plots for each family, as shown in Figure 8.12. The curve was constrained so that CRS values could not increase over time, representing the deterioration trends without rehabilitation activities being performed (*19*). Analysis of the initial curves showed the project team a distinct “flat spot” in the deterioration

IDOT typically schedules pavement sections for rehabilitation. The impact of this flat spot on programming was significant, in that it kept pavement sections from

actual deterioration trends of the State’s pavements, so a new approach was developed for the deterioration models.

The new method involved plotting the historical CRS ratings over the life of each

section, were prepared for each of the family divisions used in the previous approach and summarized in the previous table. This method appears to be unique because it

location of the CRS values with respect to age, as in the previous method. The average slope of the trajectories was calculated for each family, representing the annual

translated into deduct points so that future condition projections could be made for the Interstate and Primary pavement network. An example of a plot with the average slope

Figure 8.12 **fourth degree polynomial regression model.**

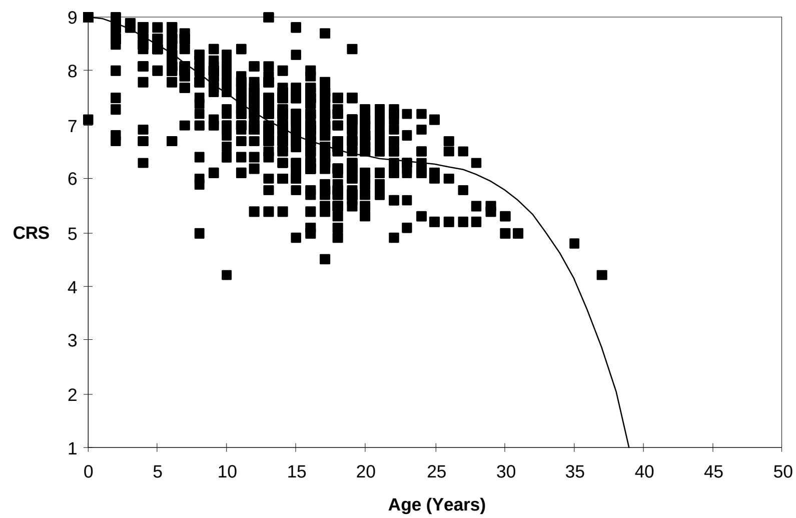
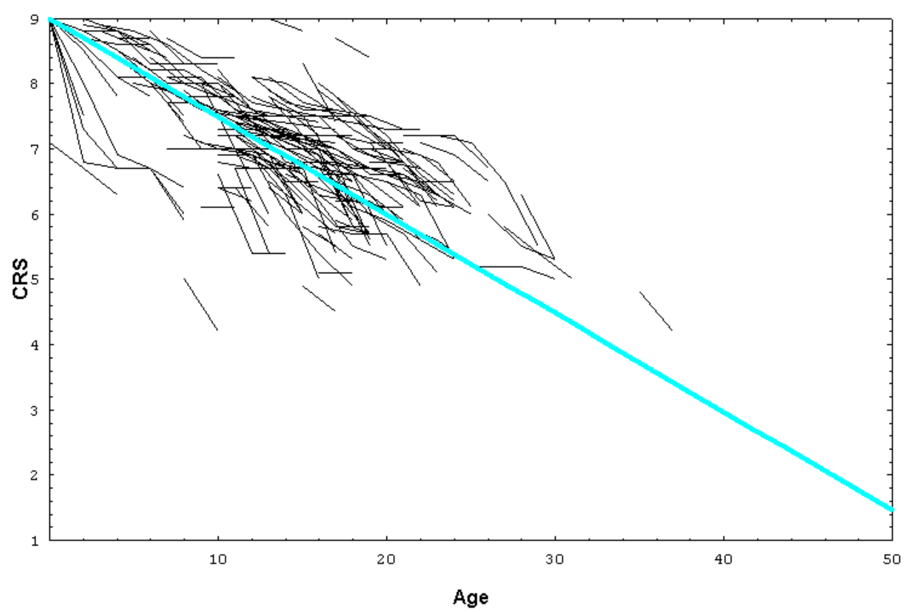


Figure 8.13 Pavement section trajectories and the resultant model from a regression analysis.



Some adjustments were made to the performance models if the pavement exhibited any signs of D-cracking, or if the pavement was known to be overlaid over a D-cracked pavement. The following adjustments are made for D-cracked pavements or D-cracked susceptible pavements.

- Asphalt concrete overlays over concrete pavements: deducts were increased by 20%.
- Jointed reinforced concrete pavements: deducts were increased by 20%.
- Continuously reinforced concrete pavements: deducts were increased by 50%.

KANSAS' PROBABILISTIC PERFORMANCE MODEL (*16*): A Markov decision process was used as the basis for a PMS developed for the Kansas DOT (KDOT). The prediction of pavement performance for this system requires the estimates of the transition probabilities, $p_{ij}(a_k)$, of going from condition state i to j in one year if action a_k is applied at the present time, for all i, j, and k. After conducting annual pavement condition surveys for several years, the transition probabilities can be directly determined from the field data. In the interim, however, the probabilities were estimated based on subjective opinions of experienced KDOT personnel.

The KDOT system considers three types of pavement distresses for asphalt pavements: roughness, transverse cracks, and block cracks. Experience and previous research indicate that the different distress types can be assumed to develop independently of each other. Hence, it was reasonable to develop the transition probabilities for the three distress types separately. This example describes only the assessment transition probabilities for the prediction of transverse cracks.

Since the assessments were subjective, they would be expected to vary from one individual to another. In order to increase the reliability of these subjective estimates and to incorporate different viewpoints, a group of fourteen KDOT personnel, experienced in observing and evaluating pavement performance in different parts of Kansas, was selected. The process of obtaining the necessary assessments from this group and analyzing the responses of the multiple assessors are discussed in the following paragraphs.

A decision analyst familiar with the procedures to elicit expert opinions assumed the responsibility for obtaining the necessary subjective estimates from the group of the fourteen assessors. After discussing several potential variables that were judged to be correlated with the occurrence of transverse cracks, the following were selected to be the most significant influence variables.

- Type of rehabilitation action
- Average daily loading (ADL in terms of daily 18-kip equivalent axles)
- Functional class
- Transverse cracks at present time
- Change in transverse cracks during previous year
- Index to the first transverse crack

The variable “index to the first transverse crack” is used to differentiate the expected life cycles of alternative rehabilitation actions. An action with a higher expected life cycle should perform better. The change in transverse cracks during the previous year is used to represent many factors (such as environmental conditions, drainage, base and subbase conditions, and material properties) which affect the occurrence of transverse cracks. If the transverse cracks on a particular pavement has increased significantly in the previous year due to one or more of these factors, a greater progression of transverse cracks would also be expected during the next year if no rehabilitation action is taken.

The decision analyst designed an assessment form to facilitate the recording of the subjective estimates made by each assessor. The form basically listed different combinations of the influence variables noted above and posed the following question for each combination:

- If 100 road segments at a given level of transverse cracks are considered, how many of them will be in each of the specified levels of transverse cracks one year after the application of a specified rehabilitation action a_k ?

A group meeting of the fourteen assessors was organized in which the analyst explained the need for obtaining the inputs from the assessors and the specific assessment question which the assessors were required to consider. In order to establish a uniform understanding, all the factors involved in the assessment were defined. Slides of pavements in different distress states were presented so that the assessors would be able to form a mental image of pavement conditions for which they were asked to estimate future performance. Some illustrative assessments were made in front of the group to point out the thinking that should go into the assessments of transition probabilities and to indicate the trends that should be followed in making assessments; for example, worse pavement performance would be expected with higher traffic loading and greater change in cracking in the previous year. Several questions regarding the definitions of different distress types and rehabilitation actions were raised by the assessors. These were discussed at some length. Copies of blank assessment forms were provided to the assessors at the end of the group session. The assessors were asked to complete the forms in two to three weeks and return them to the analyst. The data were then analyzed.

Multiple responses were generated for each transition probability since it was estimated by several assessors. The objective of the data analysis was to determine a single parameter that would be used to represent the group consensus. Out of several potential parameters (such as mean, median, or mode), the median was selected because the median is not as sensitive as the other parameters to any extreme values in the distribution.

Before calculating the median, the data were examined for consistency. Any responses which showed any obvious inconsistency (such as better performance with the do nothing alternative than with a rehabilitation action) were eliminated. This occurred very infrequently verifying that the assessment questions were properly understood by the assessors. Any isolated responses which were completely disjointed, i.e., significantly separated from the majority of the responses were also eliminated. The advantage of having a large group of assessors was that even after eliminating any inconsistent responses, at least eight to ten responses could be used to arrive at a group consensus. This provided an adequate statistical database for determining a central tendency parameter such as the median.

At the completion of the data analysis, a consensus set of transition probabilities was obtained. These probabilities were used in a network optimization model developed for the PMS. The results indicate that the performance projections under alternative rehabilitation actions seem to be consistent with previous experience and that the optimal choices of rehabilitation actions make intuitive sense. As more condition surveys are conducted, the interim set of transition probabilities are expected to be updated by combining the subjective estimates of the probabilities with the field data.

One significant benefit of the procedures used to develop the subjective performance prediction models has been the involvement of KDOT personnel from different divisions including design, maintenance, planning, research, and construction. Personnel both from the headquarters and the district offices participated in the group sessions. This has created a sense of being involved in the process of designing and implementing a PMS. This is expected to improve the acceptance of the system particularly by the district engineers who are the eventual users of the system.

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MODULE 9

REMAINING SERVICE LIFE

9.1 Introduction

The Remaining Service Life (RSL) of an individual pavement section is literally the number of years that section is expected to last until it becomes unserviceable. The RSL of a new pavement is equal to its design life (*1*,*2*). RSL analysis is concerned with examining the distribution of RSL in a pavement network.

An RSL analysis involves two distinct steps. Step one requires the agency to calculate the RSL for each pavement section in the network and to examine how the RSL is currently distributed over the entire network. Step two requires the agency to examine how the distribution can be changed in the future over the network by applying different levels of effort.

To calculate the RSL for a pavement section the agency needs the following information. (1) its current condition, (2) a definition of unserviceable condition, and (3) a mechanism to predict the deterioration of the pavement's condition. Other modules in this course cover issues (1) and (3) in great detail (see Module 6: Condition Indices, and Module 8: Performance Models.) Therefore, rather than repeat them, this module will discuss the essence of each issue and will give illustrations of how they can be used to perform the first step of a Remaining Service Life analysis.

To examine how the distribution of RSL for a pavement network can be changed in the future, the agency must perform the following tasks. (1) define a cost matrix showing the cost of moving a pavement section from one RSL category to another, and (2) test different levels of effort on the network (i.e., how many and what kinds of treatments should be applied) and how these different levels affect the distribution.

9.2 Definitions

To perform a Remaining Service Life analysis, an agency must carefully define certain components in a certain order. First, the agency must define "unserviceable" in terms of a *Threshold Value* for each pavement condition. Second, the agency must define the mechanisms it will use to measure pavement conditions. Third, the agency must define performance curves which will predict the condition until it reaches the unserviceable level. Fourth, the agency must define RSL categories. Fifth, the agency must define a cost matrix that gives the cost of moving a pavement section from one RSL category to another. Each of these components is discussed below:

THRESHOLD VALUES: One of the most fundamental definitions required for a remaining service life analysis defines *when* a pavement is considered unserviceable. Unfortunately, there is no universal definition of this. Each agency must examine its objectives and must determine a level of condition below which the pavement is considered unserviceable. For example, an interstate pavement may be considered unserviceable, if it has a rut depth exceeding 6 mm (0.25 in.); whereas, a local road may be considered unserviceable if its rut depth exceeded 12 mm (0.50 in.) or 18 mm

(0.75 in.). Still further, some agencies will not even consider rut depth in its definition of unserviceable for certain types of roads.

The main question requiring an answer when defining *Threshold Values* is, "What condition(s) does the agency consider the pavement to reach the end of its service life?". This decision is entirely an engineering decision which must be made in isolation of how much money is available to fix unserviceable pavements. There is a significant difference between how many pavements ARE unserviceable, and how many pavements the agency WILL TOLERATE in unserviceable condition. The first is a fact that is measured objectively, while the second is a policy that can be influenced by many things including funding (as will be demonstrated later).

To define the *Threshold Value* the agency must determine the following:

- The measures of condition that can make a pavement unserviceable. This can be done by answering questions such as the following. Can deformations such as rut depth make a pavement unserviceable? Can cracking make a pavement unserviceable? If so, what types of cracking? Can roughness make a pavement unserviceable? Can lack of strength make a pavement unserviceable?
- The *Threshold Value* for each of the above measures of condition. That is, the point at which the pavement becomes unserviceable. This will invariably be a function of the type of pavement and the function it is intended to provide. For example, functional class is almost always used to define different *Threshold Values*.

Current Condition: After the agency has determined which pavement conditions are used to define unserviceable, the agency needs to measure the current state of each pavement in terms of those conditions. Measuring pavement condition for a Remaining Service Life analysis is no different than for any other kind of PMS analysis (see Module 6: Condition Indices). The basic idea is to capture the current state of a pavement in terms of the conditions being measured.

Performance Prediction: Once the current state of each pavement section's condition has been measured, the future deterioration of that condition must be predicted. This too is no different that predicting the future performance for any other kind of PMS analysis (see Module 8: Performance Models.) The basic idea is to have a performance curve for each condition index that can be used to predict when that condition will reach the Threshold Value.

RSL Categories: To show the distribution of RSL over the network it is convenient for an agency to develop a set of RSL categories. These categories assemble the pavement sections into logical groups. For example, Category I could be for pavements with a zero RSL, Category II could be for pavements with 1 to 5 years RSL, Category III could be for pavements with 6 to 10 years RSL, Category IV could be for pavements with 11 to 15 years RSL and Category V could be for pavements with more than 15 years RSL. Although the categories can group RSL in any way, five year groupings are the most common.

The RSL Cost Matrix: To take the RSL analysis to its second step, the agency must develop treatments that can address different levels of RSL. This is more abstract in an RSL analysis than identifying treatments for other forms of PMS analysis. In other forms of PMS analysis the agency identifies a specific list of treatments and determines their costs and triggers. In an RSL analysis the agency must simply develop what is called a cost matrix. The cost matrix does not identify a specific list of treatments, rather, it identifies an estimation of the cost to move a pavement from one RSL category to another. The agency typically develops a different cost matrix for each class of pavement.

Table 9.1 illustrates what a cost matrix for an RSL analysis looks like. Notice that the rows in the matrix identify the FROM category and the columns identify the TO category. In other words, the cost cell "CII-IV$" represents the average cost (in $/lane-mile) of moving a pavement section from RSL Category II to RSL Category IV. The cells along the diagonal of the matrix are labeled with a prefix of "M." This is used to say that these are the "maintenance" costs for keeping a pavement in that RSL category. The cells below the diagonal are labeled "n/a" because they are not applicable since in theory one cannot move a pavement down an RSL category.

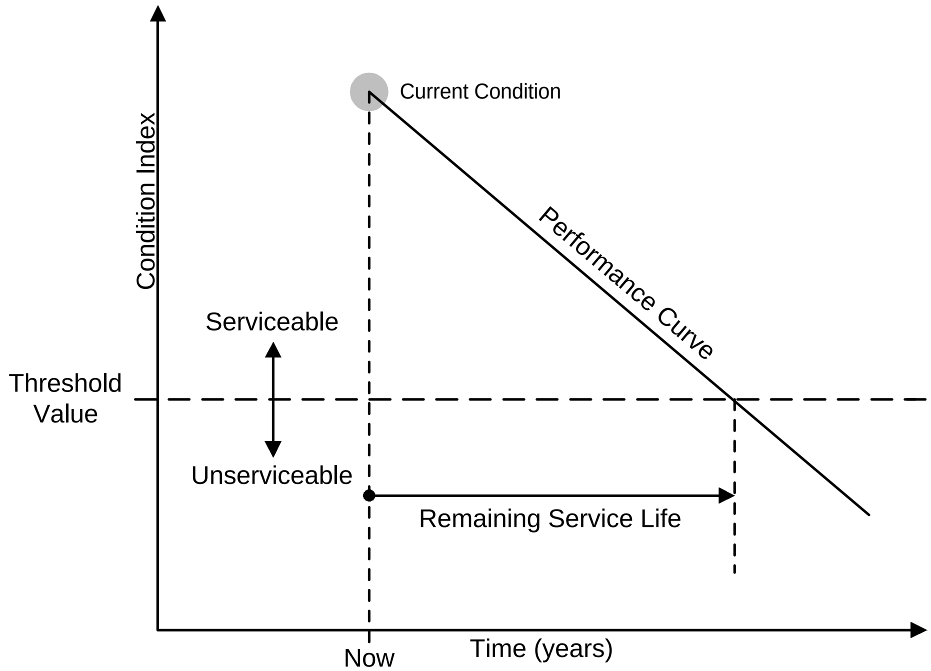
Table 9.1 **Example of an RSL Cost Matrix for a specific class of pavement.**

FROM\TO	Category I	Category II	Category III	Category IV	Category V
Category I	MI$	CI-II$	CI-III$	CI-IV$	CI-V$
Category II	n/a	MII$	CII-III$	CII-IV$	CII-V$
Category III	n/a	n/a	MIII$	CIII-IV$	CIII-V$
Category IV	n/a	n/a	n/a	MIV$	CIV-V$
Category V	n/a	n/a	n/a	n/a	MV$

9.3 The RSL Analysis

CALCULATING RSL FOR A PAVEMENT SECTION: The first part of the first step in an RSL analysis is for the agency to calculate the RSL for each pavement section. To do this the agency must have defined the Threshold Values, the condition indices and, the performance curves. Figure 9.1 illustrates the concept of calculating the RSL on a pavement section for an individual condition index. Notice how the performance curve is used to predict when the current condition index will deteriorate to cross the Threshold Value for this condition index. The time it takes for this to happen is the RSL for that condition index on that pavement section.

Figure 9.1 Calculating the RSL for an individual condition index



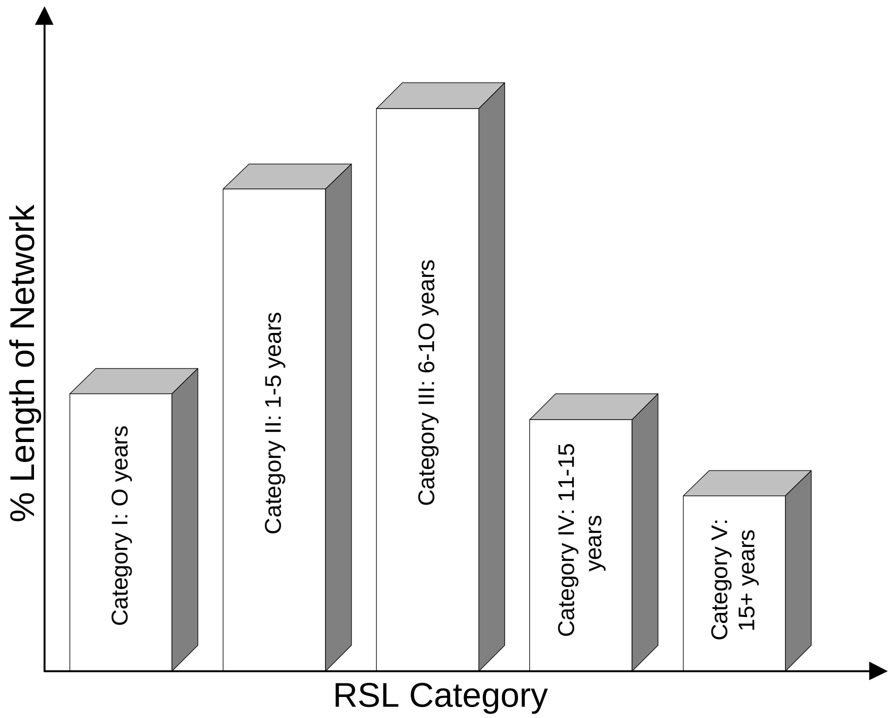
The agency must calculate the RSL for each condition index before it can calculate the RSL for the pavement section. This is because the pavement section can only have one RSL which is the minimum of all the RSL's for each condition index. By way of an example consider a doctor-patient relationship. If a patient had two years to live because of cancer and three years to live because of a heart condition, the doctor would tell him he had two years to live. That is, the patient's remaining life is the minimum of the two, not the sum or the average. Using similar logic, one can deduce that a pavement section cannot have a negative RSL. The lowest RSL a pavement section can possibly have is zero.

Current RSL Distribution: Once the agency has calculated the RSL for each pavement section, the agency can aggregate the length of all pavement sections into each RSL category. When this is done a simple bar chart is used to illustrate the current distribution of RSL on the pavement network. A typical bar chart is shown in Figure 9.2. Various conclusions can be drawn from this bar chart not the least of which is that this example network is in trouble; more than three quarters of it will be unserviceable in less than ten years The more this bar chart is skewed to the right, the better the network is.

The agency can produce this distribution for the entire network, by district, by road class and so on, depending on how sophisticated the aggregations are performed. In the simplest case, only one bar chart is produced for the entire network.

Figure 9.2 **Example of the Current Network RSL Distribution**

Some agencies stop the RSL analysis at this point and use the current RSL bar chart to



make observations, draw conclusions and set policies. For example, Baladi lists the following observations among others (*3*):

- Detect at an early stage any unwanted (e.g., uneven) distribution in the RSL of the pavement network. For example, if the RSL of a large percent of the network is 5 years, then the agency should expect the work load to increase within 5 years unless something is done to even-up the distribution.
- Assist the agency in determining the type of distress that control pavement performance. That is, if the RSL of the various pavement sections is mainly controlled by one distress type (e.g., alligator cracking), then the pavement design and the asphalt mix design process need to be examined.

Other agencies, however, take the analysis to the second step which is to examine how the distribution will change in the future.

Predicting Future RSL Distribution: There are two ways to continue the RSL analysis from here. First, using another more traditional PMS, and second, performing the network level RSL analysis with a spreadsheet. In the first case, the agency modifies its existing PMS to simply track the RSL of each pavement section into the future and adjust it accordingly as treatments are performed. To do this the agency's PMS must have the capability of attaching a design life property to each treatment. Then, as the treatment is applied the PMS must replace the RSL of the pavement section with the design life of the treatment in the year it is applied. The PMS must also have the capability of plotting the RSL distribution in the future after the selected strategies have been applied to each section. Although this sounds simple, there are only a few PMSs that do this.

The second approach can be performed by the agency using a spreadsheet, the cost matrix defined earlier and a few simplifying assumptions. This second approach is explained here.

First, the following assumption is made: "The total number of roads in an RSL category is evenly distributed." By making this assumption we can "move" the bars proportionally for each year we go into the future. For example, if Category II had 25% of the length of the network, then 5% would have an RSL of 1, 5% an RSL of 2, and so on. Each year we go into the future we can move the respective % into the next lowest RSL category. Table 9.2 illustrates this concept.

Table 9.2 Illustration of how the % in each RSL category changes over time when nothing is done

	% of lane-miles in each RSL Category			
	Now	Next Year	After 5 Years	After 10 Years
Category I	**10**	**15** (= 10 + 25/5)	**35**	**65**
Category II	**25**	**26** (= 25 - 25/5 +30/5)	**30**	**25**
Category III	**30**	**29** (= 30 - 30/5 + 5/5)	**25**	**10**
Category IV	**25**	**22** (= 25 - 25/5 +10/5)	**10**	**0**
Category V	**10**	**8** (= 10 - 10/5)	**0**	**0**

The simplest thing to do with the bar chart is to predict what will happen if nothing is done to the network after a certain period of time. Table 9.2 shows how the bar chart will look after one year, five years and ten years if nothing is done on the network. In general, a 20,000 lane-mile pavement network looses 20,000 lane-mile-years of RSL every year, if nothing is done.

The agency can perform a simple iterative analysis to determine the costs and results of performing rehabilitation on the pavement network. This is done using a Construction Effort Matrix. Table 9.3 illustrates what a Construction Effort Matrix looks like. This matrix allows the agency to specify what level of effort (in terms of lane-miles of work) they will carry out on the various RSL categories. For example, the cell labeled EII-V is where the agency says how many lane-miles will be moved from RSL Category II to RSL Category V in each year. The cost of this work is calculated by multiplying EII-V by CII-V$ from the corresponding cell in the RSL Cost Matrix.

Table 9.3
An example of a Construction Effort Matrix used in a Future RSL Analysis

FROM\TO	Category I	Category II	Category III	Category IV	Category V
Category I	n/a	EI-II	EI-III	EI-IV	EI-V
Category II	n/a	n/a	EII-III	EII-IV	EII-V
Category III	n/a	n/a	n/a	EIII-IV	EIII-V
Category IV	n/a	n/a	n/a	n/a	EIV-V
Category V	n/a	n/a	n/a	n/a	n/a

For example, assume the matrix in Table 9.2 represented the RSL distribution of a 100 lane-mile road network (100 is used to keep the example simple). Also assume that the agency made the cell EII-V = 10 lane-miles and all other cells equal to zero in the

Construction Effort Matrix of Table 9.3. Table 9.4 illustrates how the next year distribution for RSL would change. The values shown in bold in the Next Year column of this table are the values that are different than the corresponding values from Table 9.2. The following changes are noted:

- The amount of road deteriorating from Category II to Category I has changed from 25/5 to 15/5 because 10 lane-miles are removed from Category II at the beginning of the year.
- 10 lane-miles are removed from Category II and added to Category V representing the roads being moved.

Table 9.4 Example of fixing 10 lane-miles of RSL Category II to RSL Category V

	% of lane-miles in each RSL Category	
	Now	Next Year
Category I	10	**13** (= 10 + **15/5**)
Category II	25	**18** (= 25 - **15/5** + 30/5 **- 10**)
Category III	30	29 (= 30 - 30/5 + 25/5)
Category IV	25	22 (= 25 - 25/5 + 10/5)
Category V	10	**18** (= 10 - 10/5 **+ 10**)

The agency can have an experienced spreadsheet user set up this analysis on a spreadsheet. Once the setup is complete the agency can test various levels of effort by changing the Construction Effort Matrix and examining the results. This affords great flexibility in determining the cost and impacts of various construction programs.

9.4 Practical Considerations

The reliability of step one of the RSL analysis are a function of the reliability of the measured pavement condition and the performance prediction. This problem, however, is not limited to RSL analyses nor is it a new problem; it exists and has existed for all forms of PMS analyses.

The single biggest problem with the RSL analysis occurs because of a misconception about step two. Notice that by moving from step one to step two we moved from examining individual pavement sections to examining the network as a whole. Users often do not understand the results of step two cannot be directly applied to an individual pavement section. This is because the Construct Effort Matrix does not refer to specific sections; it only refers to fixing a portion of roads in the specific RSL Category. The agency still needs a process of identifying which of the road sections in each RSL Category will be fixed.

9.5 Future Trends

With the growing popularity of using the RSL as management information there is a trend to include the RSL as a part of a comprehensive PMS analysis. The concepts presented in step one of the RSL analysis are easy to implement once the agency has the required ingredients (condition indices, threshold values, performance curves, and design lives). In the future we will see RSL values being “carried along” with life-cycle costing calculations to provide more powerful pavement management information.

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MODULE 10

PRIORITIZATION

10.1 Instructional Objectives

This module introduces the principles of a multi-year prioritization analysis as part of an agency's pavement management activities. Each of the components included in a multi-year prioritization analysis are presented and discussed. Examples from highway agencies using multi-year prioritization are also presented. Upon completion of this module, the participant will be able to accomplish the following:

a) Describe the objectives of a multi-year prioritization analysis.
b) Understand the differences between other multi-year analysis techniques.
c) Describe the components of a multi-year prioritization analysis.
d) Understand the use of a multi-year prioritization analysis as part of an agency's project selection process.

The material used to develop this module has been extracted from the FHWA Demonstration Project 108A course materials on Multi-Year Prioritization (*1*).

10.2 Introduction to Multi-Year Prioritization

Multi-Year Prioritization (MYP) is a pavement management process used to objectively identify the best combination of projects over a multi-year period. Each agency using a MYP analysis must provide its own definition of what constitutes the *best* combination of projects, but most agencies using MYP evaluate projects in terms of cost-effectiveness or benefit to the agency. Each agency must also evaluate its ability to implement the best combination of projects. In most agencies, real world issues such as political influence and other outside pressures often effect the final combination of projects included in a multi-year program. For that reason, MYP is considered a tool to provide information to assist the decision-maker in selecting the most appropriate projects for the program. The analysis results should not be considered the final program by an agency using these techniques.

Using the techniques discussed in this module, agencies will be introduced to the tools necessary to develop a process that helps allocate limited resources in an efficient and cost-effective way over a multi-year period. These techniques provide the information necessary to evaluate the long-term impacts of various rehabilitation strategies through an evaluation of the following:

- The timing of rehabilitation actions.
- An economic analysis of feasible maintenance and rehabilitation alternatives.
- The predicted impact on the network over time for each combination of projects over a given analysis period.

MYP is most beneficial to an agency that has needs that exceed the amount of money available to maintain the network. In other words, MYP can benefit most agencies responsible for the management of a deteriorating highway or roadway network, especially those in which limited funds are available.

Benefits Provided by Multi-Year Prioritization: Because a MYP analysis evaluates the most appropriate combination of projects, treatments, and application timings for a specific budget level over a fixed analysis period, it provides the agency with the information needed to evaluate the cost-effectiveness and long-term impacts of each possible multi-year program. An agency is able to evaluate the long-term impacts of accelerating or postponing projects from one program year to another, or modifying budget levels in each of the analysis years included in the program.

MYP also provides the user with the ability to evaluate various overall program development strategies, such as selecting projects on a worst-first basis versus selecting projects that provide the highest benefit/cost ratio. Additionally, the analysis tools provide the ability to evaluate the budget requirements to implement various agency policies, such as maintaining the interstate highway system above a particular condition level.

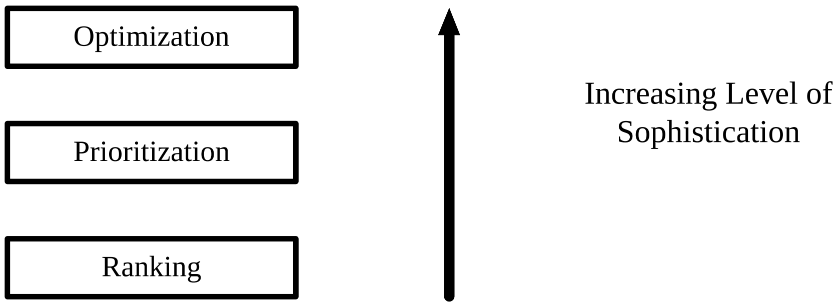
These capabilities provide an agency with a number of benefits beyond those provided with a basic PMS program. These benefits include the following:

- The ability to forecast future pavement conditions.
- The ability to analyze options for timing the application of maintenance and rehabilitation treatments.
- The ability to evaluate the effectiveness of various rehabilitation strategies for each pavement section quickly and efficiently.
- The ability to perform an economic analysis of various maintenance and rehabilitation strategies.
- The use of an objective process for considering projects for funding in a multi-year program.
- The provision of information needed by decision-makers to effectively prioritize rehabilitation projects within the available funding constraints.
- The ability to project funding needs to achieve overall agency goals, such as maintaining a particular condition level over time.

The agencies successfully using MYP analysis as part of their pavement management program have identified several other benefits realized after the implementation of the program. These agencies feel that they are better prepared to address information requests that come to them about the pavement network and that the information helps facilitate discussions between upper management, districts, and outside agencies. These agencies feel that although they are not always able to implement the recommendations from their MYP analysis, they at least understand the trade-offs they are making.

Comparisons of Analysis Techniques Such as Ranking, Prioritization and Optimization: In order to fully understand the capabilities of MYP, it is important that the differences between some of the other methods of prioritizing, or optimizing, the selection of projects and treatments for multi-year planning purposes is understood. This section briefly summarizes the characteristics of ranking, prioritization, and optimization as pavement management tools. These three techniques are presented in increasing level of sophistication, with ranking being the least sophisticated approach and optimization being the most sophisticated, as shown in Figure 10.1. The objectives of each of the three types of analysis are presented.

Figure 10.1 Increasing level of sophistication in analysis techniques.



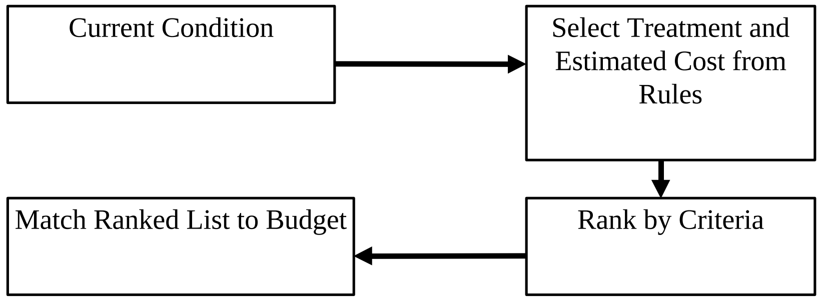
Ranking: Perhaps the simplest form of prioritizing projects is to rank pavement maintenance and rehabilitation needs based on either engineering judgment or a measured parameter such as condition. Each year, the pavements are ranked in accordance with the ranking guidelines until the amount of money available for maintenance and rehabilitation projects is used up. In the next year, the process is repeated. In some cases, the ranking factor may actually be weighted by additional factors of importance to the agency, such as traffic levels or functional classification. In some cases, ranking is also referred to as single-year prioritization.

The most common ranking criteria in highway agencies include the following (*3*):

- Rank by condition
- Rank by initial cost
- Rank by cost and timing
- Rank by life-cycle cost
- Rank by benefit/cost ratio.

In most instances, the current condition of the pavement, or the distresses present in the most recent condition survey, are used to identify the feasible maintenance and rehabilitation strategies for each pavement section. One or two treatments are identified for each possible condition level and the actual field conditions are matched to the agency prescribed treatments. After each treatment has been assigned to a pavement section, the cost of the project can be calculated so that the highest priority projects can be matched to the budget levels available. This process is illustrated in Figure 10.2.

Figure 10.2 Ranking process.



For example, assume an agency has the pavement sections shown in Table 10.1 in its network. Further assume that the condition values included in the table reflect the results of the most recent condition surveys for the network. Maintenance and rehabilitation strategies are then assigned to each section based on the current condition and the types of distress present. The costs for each project can then be calculated by multiplying the area of each project section by the unit cost for the preferred treatment.

Table 10.1 Sample network.

Section ID	Condition Level	Treatment	Cost (millions)
Route 67, from Milepost 1-4.9 (67A)	67	Minor	1
Route 67, from Milepost 5-9.9 (67B)	82	Preventive Maintenance	0.5
Route 67, from Milepost 10-13.5 (67C)	52	Major	3
Route 14, from Milepost 1-3.9 (14A)	71	Minor	2
Route 14, from Milepost 4-5.9 (14B)	74	Minor	1.5
University Avenue, between Lincoln and Sixth (Univ1)	85	Preventive Maintenance	0.5

Using a simple ranking procedure based on addressing the worst pavements first, the ranked list presented in Table 10.2 would be prepared.

Table 10.2 Simple ranking results.

Section ID	Ranking	Treatment	Cost (millions)
Route 67, from Milepost 10-13.5 (67C)	1	Major	3
Route 67, from Milepost 1-4.9 (67A)	2	Minor	1
Route 14, from Milepost 1-3.9 (14A)	3	Minor	2
Route 14, from Milepost 4-5.9 (14B)	4	Minor	1.5
Route 67, from Milepost 5-9.9 (67B)	5	Preventive Maintenance	0.5
University Avenue, between Lincoln and Sixth (Univ1)	6	Preventive Maintenance	0.5

Projects are selected from the ranked list until the available funding levels are depleted. In this example, if it is assumed that each project cost $1 million dollars to repair, and the agency had an available budget of $4 million, the first two projects would be funded.

A slightly more sophisticated version of the ranking process would include a weighting factor to reflect other important factors such as traffic levels. In this instance, the agency would consider condition levels and traffic levels in establishing the ranked list. For example, assume that the agency assigns a weighting factor of 0.5 to sections with high traffic levels, 1.0 to sections with average traffic, and 1.5 to sections with low traffic. By multiplying the condition index by the traffic factor, a new ranking number is developed. The assumed traffic weighting factors and revised rankings are included in Table 10.3. In this case, a $4 million dollar budget would fund sections 14A, 14B, and Univ1. The third ranked project, 67C, was not funded because the funding required for the project was not available after the first two priorities had been addressed.

Table 10.3 Traffic weighting factors and revised rankings

Section ID	Ranking	Condition	Traffic	Weight	Cost (millions)
14A	1	71	0.5	36	2
14B	2	74	0.5	37	1.5
67C	3	52	1	52	3
67A	4	67	1	67	1
Univ1	5	85	1	85	0.5
67B	6	82	1.5	123	0.5

Ranking techniques are fairly easy to use and can often be done using a spreadsheet. This technique is limited in the amount of information available regarding the impact of different choices on network conditions, and no consideration is made for the rate at which sections are deteriorating because no performance models are developed. This method also fails to take into account different rehabilitation approaches for each project. Unless a benefit/cost ratio is used to determine the ranking order, there is also no consideration of different economic strategies or the benefits provided to the agency.

Single-Year Prioritization: Many agencies use a ranking process as part of their project and treatment selection process. Although the process results in the development of multi-year plans and programs, many agencies are not actually using a MYP analysis. Instead, many agencies are using single-year prioritization to develop multi-year plans. Because of this, many agencies that believe they are realizing the benefits of MYP are not gaining all the benefits possible.

Single-year prioritization is generally another term for ranking. Using any type of prioritization (or ranking) process, such as condition, initial cost, life-cycle cost, or benefit/cost ratio, the most beneficial projects are identified in each year of the analysis. The primary difference between this approach and true MYP is *in the lack of consideration of treatments in alternate years in addition to the consideration of alternate treatments*. While single-year prioritization may consider the most effective of a number of feasible treatments, it rarely considers each feasible treatment in each of the analysis years. Because of this, the users of a single-year prioritization do not determine the relative benefit of applying a less costly alternative in an earlier year compared to a more expensive alternative in one of the later years of the analysis. Similarly, the long-term impacts of delaying or accelerating projects from one year to another can not easily be evaluated.

Agencies using a single-year prioritization (or ranking) process consider this approach to be a tool that assists in addressing the agency's most pressing projects first through a somewhat objective process. Because the approach is simple to explain and logical for agencies with a large number of unaddressed rehabilitation needs, this approach is often used to justify expenditures to managers and legislatures.

Although this approach is somewhat objective, it does have serious drawbacks that should be understood by any agency using this technique. First of all, no alternative treatments or treatment timings are considered so the long-term impacts of the decisions are not adequately considered. Secondly, most agencies using this approach address the pavements in the worst condition first, forcing the agency to continue to operate in the mode of fighting fires. Finally, because the long-term impacts are not evaluated, the agency has no way of evaluating the true cost of their rehabilitation approach over time. As a result, an agency could be continuing to add to its problem without knowing that alternative approaches may provide better long-term solutions.

Multi-Year Prioritization: MYP is a more sophisticated approach to project selection that approaches a truly optimized solution for addressing the needs in a pavement network. Prioritization techniques use mathematical modeling tools to achieve the best combination, over a specified period, of the following:

- the projects in the network to receive reconstruction, rehabilitation, or maintenance,
- the particular treatments to be applied to each of the selected projects, and
- the most effective timing for applying the appropriate rehabilitation.

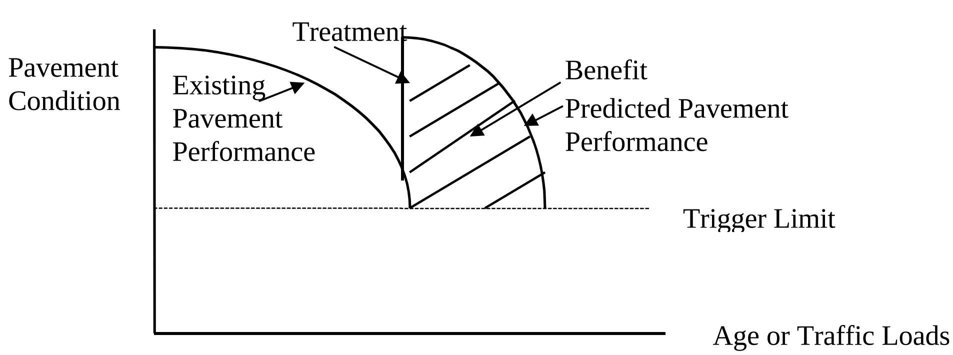
This method requires the use of performance prediction models, or remaining service life estimates, to measure the effectiveness of a particular project into the future. It also requires the definition of trigger levels to identify needs, and provisions that allow the acceleration or deferral of treatments during the analysis period. The use of a computer program is also recommended to quickly evaluate the trade-offs between the alternatives considered.

Agencies using prioritization for project selection purposes generally identify some method of evaluating one strategy over another. There are two common approaches used to perform this prioritization. These include the following:

- Cost-effectiveness approach.
- Benefit/cost approach.

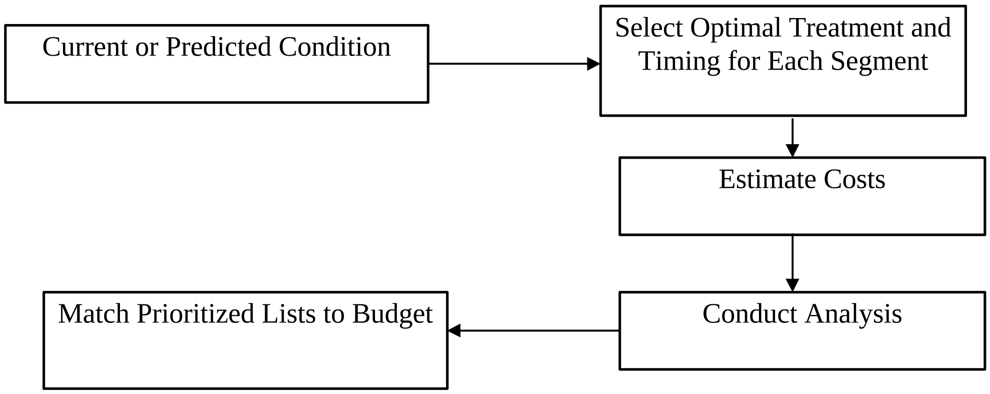
In many cases, the agency uses some form of cost-effectiveness to evaluate one treatment over another, or one year over another. A more common approach is to use a benefit/cost ratio to compare the benefit to the agency, per unit cost, for each option available. Benefit is typically estimated as the additional life provided by the application of a particular treatment, as shown in Figure 10.3. The cost of the treatment, in terms of initial cost or life-cycle cost, is also defined and divided into the calculated benefit to determine the benefit/cost ratio. The recommended treatment or project timing is then identified as the treatment that provides the highest benefit/cost ratio, or the highest incremental benefit/cost ratio.

Figure 10.3 Calculation of benefits.



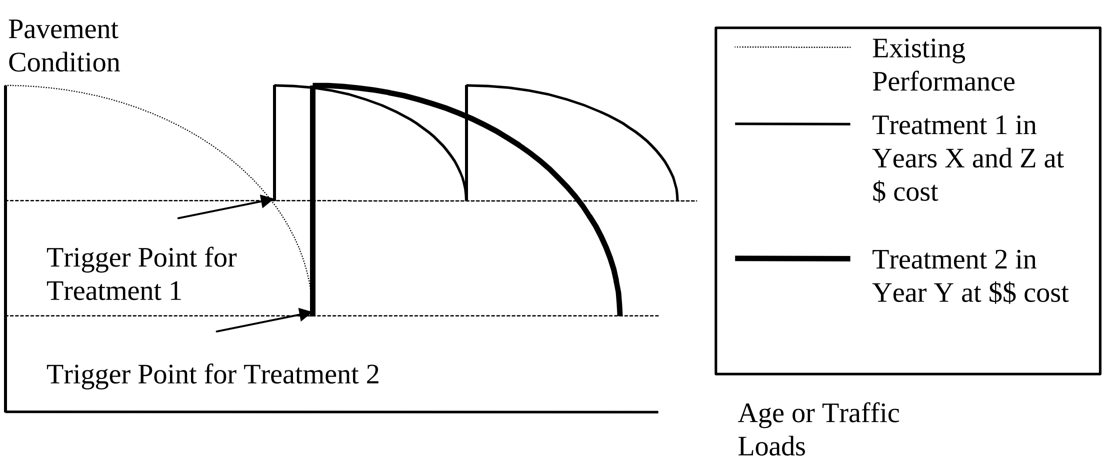
With a prioritization process, the project selection process takes place after the recommended treatment or timing has been identified for each section needing maintenance or rehabilitation. After these decisions have been made, the projects are prioritized and the multi-year program is developed by matching program needs to available funding levels. This process is illustrated in Figure 10.4.

Figure 10.4 **Multi-year prioritization process.**



As Figure 10.4 illustrates, a prioritization process considers the application of the preferred treatment for each year in the analysis, within the financial constraints anticipated by the agency. This analysis can include the consideration of a large number of options in each analysis year, which is why this type of analysis lends itself to a computer. This concept is simply illustrated in Figure 10.5 for one pavement section. A network-wide analysis can quickly become unmanageable without a computer program.

Figure 10.5 **Types of treatments options considered in MYP.**



In most cases, the projects that provide the greatest benefit to the agency or its users will have a higher priority in the program development process. Some agencies have incorporated prioritization schemes into their pavement management systems to better tailor the project selection process to reflect real life priorities. For example, although a county road may be the most cost-effective project for an agency, public pressure may force the selection of an interstate project long before the county road project is funded.

While it is realized that these types of adjustments must be made within an agency, a fully functional prioritization system can provide the agency with the information needed to fully understand the impacts of these decisions on the long-term condition of the pavement network, or the future maintenance and rehabilitation needs.

Differences in Multi-Year Prioritization and Ranking: MYP differs from a ranking process in a number of ways. First, in most cases, a number of different treatment alternatives are considered in MYP. The use of a benefit calculation generally identifies the treatment that provides the most benefit to an agency while a ranking approach typically considers only one assigned option for a specified condition level. Another difference lies in the sophistication of the analysis. In a ranking situation, the most common factors considered are the current condition and the existing traffic levels. In a MYP, an agency is able to simulate future conditions through the use of performance models so that future traffic levels, expected performance of various treatments, and other factors can be considered in the analysis.

MYP analyses closely represent the solutions obtained from a true optimization analysis. Dr. Robert Lytton has demonstrated that several heuristic approaches, such as a MYP approach using an incremental benefit/cost analysis, provide solutions similar to an optimized approach such as dynamic programming. This is because both algorithms go through a similar sequence of decisions to determine the set of alternatives and projects that provide the greatest benefit for the total amount of money spent (*7,10*). For this reason, many agencies refer to MYP as an optimization technique.

The literature identifies the following advantages and disadvantages of MYP over single-year prioritization (or ranking) (*9*).

<u>Advantages</u>

- The option of timing of rehabilitation, reconstruction, or maintenance can be included in the process.
- The capability of finding an optimum combination of projects, alternatives, and timing for any budget level can be incorporated.
- The ability to set targets for future levels of serviceability, or other strategic purposes, is possible.
- The impacts of various funding levels can be assessed.

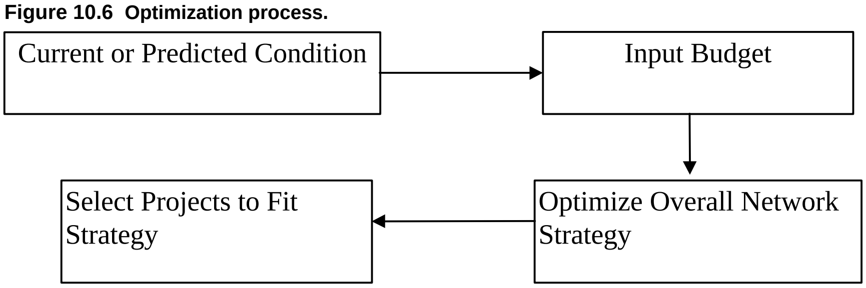
<u>Disadvantages</u>

- It is more complex than single-year prioritization.
- The believability of the results is dependent on the reliability of the performance or deterioration prediction models.

Optimization: The use of true optimization models is perhaps the most sophisticated form of multi-year analysis. Through the use of mathematical programming methods, including linear, non-linear, integer, and dynamic programming, optimized solutions are developed in accordance with goals established by the agency. Very simply, an agency using optimization models would select something to optimize such as the maximum total benefit to the agency or the lowest rehabilitation cost to achieve certain condition levels. The agency would also identify any resource constraints that may affect the analysis.

Optimization considers the goals of the organization and uses mathematical programming techniques to find overall network strategies that achieve the goals. This is normally conducted in a two-step process. First, the strategies that achieve the overall goals of the organization are identified. An example of a strategy might be to minimize the total costs required to maintain a desired condition level. Only after the strategy has been determined can projects be matched to the strategy. For example, if the strategy identified that 300 miles of road should be moved from condition category a to condition category b, the agency must identify segments that meet this requirement. The overall approach used in optimization is illustrated in Figure 10.6.

Figure 10.6 Optimization process.



An optimization analysis considers the optimization goal and uses mathematical programming techniques to find the best solutions from an infinite number of possible solutions. The difference between optimization and the techniques discussed earlier is that in an optimization analysis, outputs are normally provided in terms of percentage of miles that should be mobilized from one condition to another rather than the identification of specific projects. For example, the optimization analysis could recommend that in order to provide the most benefit to the agency, 30% of the pavements in poor condition should receive some type of rehabilitation to take them to good condition and 50% of the pavements in fair condition should receive rehabilitation to take them to good condition. In Kansas, for example, the optimal rehabilitation policy for a given year is provided in terms of condition states, the optimal action in each condition state, and the unit cost for each recommended action (*3*). A separate analysis is performed to identify which pavement sections in each of the condition categories should be selected to achieve the overall goal.

Agencies using optimization feel that this more complex approach addresses two important considerations that are not considered in a prioritization analysis. These considerations are identified as the following (*9*).

- The evaluation of inter-project trade-offs in selecting strategies.
- The selection of strategies which are guaranteed to adhere to budget limits.

These agencies prefer the capabilities provided through optimization for the following reasons:

- It allows trade-offs among projects, but also evaluates any number of strategy choices for each project in the course of making these trade-offs.
- It allows multi-year network level planning and programming aimed at moving the overall system towards a defined level of performance.

Although these additional capabilities are attained through an optimization analysis, some agencies have found that the results of the optimization are not understood by elected officials and upper management. Agencies reported that it is easier to defend projects and treatments selected through a ranking or prioritization process (*3*). Because the analysis results are not easily understood, some individuals perceive a loss of control in their programming and scheduling processes. This is enhanced by the fact that individuals with strong backgrounds in mathematics and statistics must be employed to conduct the analysis.

Overall Benefits Provided Through the Use of Optimization and Prioritization Techniques: Although there are a number of substantial differences in the approaches used to conduct an optimization and prioritization analysis, both approaches provide an agency with documentable benefits in terms of more cost-effective decision-making capabilities, longer service life, and greater numbers of users served adequately. It has been reported that near optimal solutions can be approximated through the use of heuristic methods such as incremental benefit/cost analysis (*7*). Heuristic approaches are simpler and more computationally efficient than mathematical programming methods, which has led to their widespread acceptance within transportation agencies. This work has demonstrated that the use of heuristic approaches can provide an agency with 20 to 40 percent more benefit than subjective project selection techniques. The use of optimization provides another 10 to 20 percent benefit *(7)*. Due to the ability of heuristic methods to closely approximate solutions using true optimization, agencies using heuristic methods often refer to their analysis as an optimization analysis.

Components of Multi-Year Prioritization: A MYP analysis is comprised of a number of different components, each of which is usually tailored to the implementing agency. These components, listed below, are explored in more detail in the following modules of the demonstration course materials. A brief overview of each of the components is provided below for informational purposes.

Performance Analysis: In order to conduct a multi-year analysis, it is imperative that a pavement performance analysis be conducted so that the deterioration rates of each pavement type are established. This information can then be used to forecast future pavement condition in order to determine the following:

- The appropriate type of rehabilitation needed in future years.
- The most appropriate timing for applying the treatment.
- An estimate of the additional life provided by the application of the treatment.
- A determination of the long-term impacts of programming decisions.

A number of different modeling tools are available for representing the deterioration trends of pavements included in the pavement network. In agencies where MYP techniques are used, deterministic models are most common.

Pavement Preservation Strategies and Treatments: One of the important functions of a MYP analysis is the selection of the preferred maintenance and rehabilitation strategies for each possible project considered during the analysis period. There are a number of different techniques used to select preservation treatments, as discussed below.

- Decision trees, featuring a series of branches that are selected based on overall condition, types of distress present, functional classifications, or other factors. Each branch eventually leads to the preferred treatment for a given set of conditions.
- Matrices, featuring tables that describe certain characteristics and the allowable ranges for particular levels of rehabilitation. The matrix may identify the preferred treatment or list a series of feasible alternatives that are considered further in terms of their effectiveness.
- Rules, including a set of rules that specify particular treatments for certain conditions.

The requirements of each of these tools, as well as the advantages and disadvantages, are discussed later in this module.

Prioritization Techniques: There are a number of different technique that may be used to conduct a MYP analysis. Unfortunately, most agencies are faced with the dilemma of prioritizing rehabilitation projects because funding levels do not adequately address all the needs of the agency. Because of that, a MYP analysis includes a network investment analysis that considers the economics of the different rehabilitation options available and helps identify the most cost-effective alternatives. In many instances, a life-cycle cost analysis is incorporated into a benefit/cost evaluation of the effectiveness of various rehabilitation options. Agencies that do not have adequate life-cycle cost data to support this type of analysis may opt to use initial costs as the basis of the effectiveness evaluation.

Project Selection Process: The project selection process involves the use of the information produced through each of the different analysis components and the development of the multi-year capital improvement plans. In some agencies, the information is provided to the District Offices where programs are developed and finalized. In other agencies, where the management is more centralized, District input is one component of the project selection process. Other factors, such as the need to balance programs among Districts, or central office priorities, also significantly influence the program development process.

No matter which approach is used, the final result is the development of a multi-year program which indicates the project limits, estimated cost, and scope of work required to address all deficiencies identified in the project. This process typically includes representatives from throughout the highway agency, not just from the pavement management office. It is imperative that the information from the project selection process be integrated back into the pavement management system so that the system remains current and viable.

Data and Analysis Requirements of Multi-Year Prioritization: Each component of a MYP analysis has individual requirements for the types of data needed to support the analysis. These data requirements vary considerably depending on the level of sophistication of the analysis, the type of condition rating system used by the agency, and the level of confidence in the data. Because of this, it is hard to identify a comprehensive list of data requirements. Having said that, some of the basic requirements of each of the technical components discussed in the previous section are outlined here. It must be understood that if an agency wishes to develop a very sophisticated approach to any of these components, more detailed information may be required.

Pavement Performance Analysis

- Inventory data (surface type, location, etc.)
- Geometry
- Age
- Historical conditions
- Current conditions
- Environmental factors
- Traffic estimates
- Materials characteristics

Pavement Preservation Strategies and Treatments

- Feasible treatment types
- Conditions under which each treatment is considered feasible
- Cost of each treatment
- Expected life of each treatment

Prioritization Techniques

- Expected life of each treatment
- Cost of each treatment (life-cycle cost or initial cost)
- Agency policies and practices

Project Selection Process

- Project limits
- Project scope (bridges, pavement needs, etc.)
- Prioritization factors
- Project costs
- Project constraints
- Available resources
- Agency policies and practices

ADVANTAGES OF MULTI-YEAR PRIORITIZATION: The agencies using MYP as part of their pavement management activities identified a number of benefits provided by this process. Although some benefits were hard to quantify, such as improved communication or more informed decision-making, others were much more tangible. Some of these benefits are outlined below.

- An automated procedure that assists in the project selection process, according to the constraints and practices within the agency.
- Improvements in the long-term effectiveness of the decision process.
- An understanding of the impacts of project timing or treatment selection on the long-term condition of the network.
- Improvements in the forecasting of future needs.

USE OF MULTI-YEAR PRIORITIZATION WITHIN A HIGHWAY AGENCY: Many agencies could benefit from the use of MYP techniques in the development of their capital improvement programs. It is evident, however, that many agencies are not able to utilize the results of a MYP process for a number of reasons, including the following:

- the presence of a management philosophy that reflects a worst-first priority,
- outside influences that may influence project selection, such as adjacent projects or political factors, and
- a large backlog of pavements below an acceptable condition level that an agency wants addressed before addressing more cost-effective measures.

In order to gain the most benefit from the use of MYP techniques, it is imperative that the agency consider the following factors:

- management must understand the philosophy behind the recommendations,
- the recommendations reflect those projects that will provide the agency with the most benefit, assuming normal conditions are met - there are no guarantees,
- different strategies can be developed to achieve different goals so the agency must strive to develop a program that addresses the right goal, and
- these techniques are nothing more than tools meant to assist the agency staff; they are not meant to replicate or replace the experience and judgment of experienced staff.

At the very least, the results of a MYP analysis should be used by the agency to compare the long-term impacts and overall effectiveness of any other program considered by the agency. In this way, the agency can fully evaluate the “true” costs of one strategy over another and determine the action that best meets the agency’s goals.

10.3 Strategy Development

One of the primary functions of a PMS is to assist an agency in the development of a multi-year capital improvement plan that identifies the pavement-related projects in each year. Multi-year prioritization is one technique that is used to establish priorities among the various pavement project needs so that the agency has the information necessary to evaluate the long-term impacts of one improvement program over another.

The capital improvement program is comprised of a listing of the pavement-related maintenance, rehabilitation, and reconstruction projects that will be funded in each of the years covered by the program. The program is normally developed through an evaluation of many combinations of projects and treatments for the budget levels expected to be in place in each program year. Although improvement plans may span one to ten years, most agencies consider the projects scheduled for the first two or three years to be fixed while projects in the later years may be accelerated, delayed, dropped, or added to the list.

There are a number of different approaches that may be used to develop a multi-year program, including strategies that look at one possible treatment for each project and those that consider two or more treatments. This portion of the course evaluates the predominant approaches used to develop rehabilitation strategies and the tools commonly used to identify treatments for each eligible pavement section.

Description of Pavement Strategy Development: Within the field of pavement management, there are many uses of the term strategy development. In some cases, a strategy may be a synonym for a treatment selected for an individual project. Other agencies may refer to a strategy as a classification of treatments (such as minor rehabilitation) to address a certain level of deterioration or type of deterioration. For this course, pavement strategy development is defined similarly to the definition provided in National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice Number 77 (*2*), as defined below.

- A pavement strategy is a plan of action comprised of the application of one or more maintenance or rehabilitation techniques designed to improve or maintain the condition of a pavement segment above some predetermined minimum requirement.

In order to be most effective, each strategy should be evaluated in terms of:

- the most appropriate timing for applying the strategy,
- its anticipated design life, and
- any physical, environmental, or economic constraints that may influence its selection.

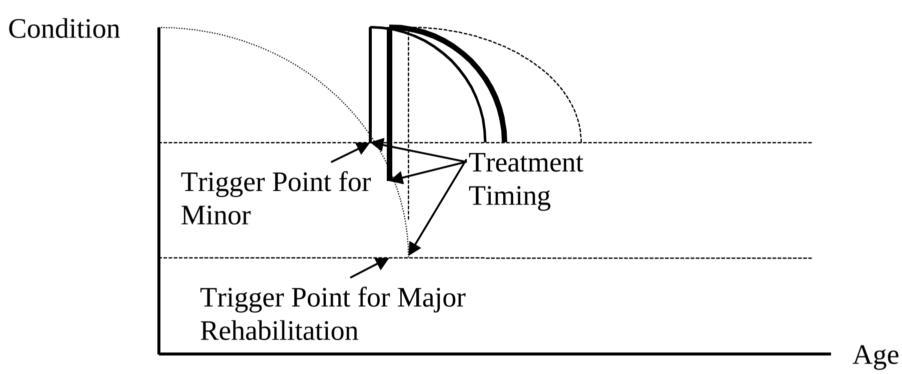
Components of Pavement Strategy Development: The development of a comprehensive pavement strategy depends on the implementation of a number of analysis components, as listed below.

- Listing of Strategy Guidelines and Treatment Options
- Costs
- Pavement Performance

One of the first components is a listing of the strategy guidelines and treatment options to be considered in the analysis. Strategy guidelines would normally consist of a series of rules that outline when a category of maintenance or rehabilitation would be feasible, or when a particular treatment might be feasible. For example, a rule may state that preventive maintenance activities are performed on pavement sections with a condition index of 80 to 100. Minor rehabilitation may be considered for pavements with a condition between 65 and 80, and so on. Within each of these repair categories, specific treatments may be considered such as crack sealing, joint filling, patching, or spall repair as types of preventive maintenance. The assignment of the appropriate maintenance activity would most likely be dependent on the pavement surface type and the distress identified as part of a condition survey.

In situations where a condition range is used to define the feasibility of a treatment or rehabilitation strategy, there are normally a number of years in which each pavement section is in each condition category. This is illustrated in Figure 10.7 which shows three possible timings for a minor rehabilitation strategy to be applied to a particular pavement section.

Figure 10.7 Different timing options for rehabilitation.



As you can imagine, consideration of each feasible treatment at each feasible point in time results in a complex analysis. For that reason, another important component of the multi-year prioritization strategy development is a computerized program to perform the analysis. The program should be capable of comparing the effectiveness of one strategy to another and the impacts of selecting each possible timing for rehabilitation. The methods normally used by the program to measure the effectiveness of these alternative strategies are discussed in the next section on network investment analysis.

Another component of the strategy development is a cost component that provides the unit costs for each of the feasible maintenance and rehabilitation treatments being considered, whether in terms of initial cost or life-cycle cost. This component is important so the cost of each possible project can be analyzed and programs can be developed for the anticipated funding levels.

The analysis of the effectiveness of each option requires that the expected performance of each treatment also be considered. For this reason, a performance component must be added to the program so that the anticipated life of each treatment can be estimated. These estimates of future condition trends may be based on the performance models already developed by the agency or on separate models developed specifically for this application. In some agencies, where new treatments are considered in the PMS, expert models must be developed to reflect expected performance since no historical data exists when a treatment is first being used.

Objectives of Pavement Strategy Development: Each agency may use the results of a pavement strategy differently, but the overall objectives of the analysis are similar: to assist in the development of improvement programs. In most cases, a pavement strategy is developed to plan the maintenance and rehabilitation program for current and future years based on the constraints that influence project selection. The impacts of each strategy can usually be produced so informed decisions can be made based on long-term results.

It should be emphasized that a PMS is an effective tool to assist in the development of an improvement program within an agency. It is not, however, singly capable of developing the final program and cost estimates. A final program strategy must be developed through an iterative process that combines the input of a number of sources, including the pavement management system, and the judgment of experienced agency personnel.

Treatment Selection as a Part of Strategy Development: Project and treatment selection within a pavement management program can be considered as two separate activities, or may be combined to be considered one part of strategy development. According to NCHRP Synthesis 77 (*2*), nearly equal numbers of state highway agencies select treatments in conjunction with the project selection process as do agencies that select the treatment after a project has been selected. In some cases, agencies stated that a preliminary treatment recommendation was made at the time of project selection but the recommendation was often revised after a more detailed evaluation of the project limits was completed.

Approaches to Strategy Development: There are two primary approaches used within a multi-year prioritization analysis for strategy development; single treatment strategy approaches and multiple treatment strategy approaches. Single strategy approaches consider each feasible maintenance and rehabilitation strategy separately, although more than one treatment could be considered feasible for each project. The effectiveness of each strategy is considered independently of any other types of treatments that may be applied in future years.

A multiple treatment strategy, on the other hand, typically consists of a series of two or more treatments over the analysis period. Instead of considering, for example, the effectiveness of a thin overlay in years two and three for a particular section, a multiple treatment strategy would consider the thin overlay in years two and three followed by another thin overlay in years seven or eight. Another strategy for the same section could be a thin overlay in years two or three followed by a thick overlay in years nine or ten.

Each of these approaches is discussed in more detail in the following sections.

Development of a Single Treatment Strategy: The most common approach to the development of a strategy considers one or more feasible treatments for each project section. Each treatment is considered independently so that the most cost-effective or beneficial treatment for a section is recommended for implementation.

The first step in the development of a single treatment strategy is to identify the feasible maintenance and rehabilitation treatments to be considered in the analysis and the rules that define the conditions under which the treatments may be applied. For example, minor rehabilitation may be an appropriate treatment for a pavement in a condition range of 75-90 (assuming 100 represents an excellent pavement), while a thin overlay may be considered for pavements with a condition between 65-80 with little, or no, structural deterioration present. Both of these alternatives may be considered feasible for pavement sections falling between a condition index of 75 and 80.

Once the treatments have been defined, and the rules for applying each treatment established, the program analyzes the impacts of each feasible treatment independently. Depending on the type of analysis used, the treatments may be analyzed in terms of the benefit provided to the agency for the cost expended, the cost-effectiveness of each alternative, or in some other way. Regardless, the most appropriate treatment for each pavement section is identified. These treatments are then typically ranked so that the most beneficial projects are matched to the available budget levels until the funding levels are depleted.

Depending on the type of analysis used, the actual project selection process can be quite complex and well beyond the scope of this chapter. The point of this section is simply to illustrate that agencies using a single treatment strategy may consider several feasible treatments for each pavement section in each year of the analysis. However, each of the treatments is considered independently of one another and independently of other treatments being considered for other sections. In most cases, the treatment and year that provides the most benefit or cost-effectiveness to an agency is identified as the most appropriate treatment to apply for the particular pavement section.

Development of a Multiple Treatment Strategy: Agencies that consider a multiple treatment strategy, on the other hand, consider a combination of treatments for each pavement section in each year of the analysis. In this type of approach, the agency identifies feasible treatments for the analysis and sets up the same types of rules for applying the treatments as with the single treatment strategy. The primary difference is that with this approach, the combination of at least two treatments in successive years is analyzed, rather than one treatment independently.

As you can imagine, the number of possible strategies increases dramatically with a multiple treatment approach. This is because the number of combinations of treatments can easily multiply. Using the example presented in the previous section, the minor rehabilitation will still be considered in each year that the pavement section condition ranges from 75 to 90. However, a subsequent treatment may also be added to form the entire strategy for a pavement section. In this case, the subsequent treatment could be additional minor rehabilitation when the pavement again drops to a condition level of 80, an overlay when the pavement drops to a 65, or reconstruction at a condition level of 40. Using this example, the original minor rehabilitation strategy became three multiple treatment strategies that must be considered in the analysis. The three strategies must be considered in each year that the initial treatment is considered feasible.

Subsequent treatments are used primarily to address the fact that the lives of most treatments is shorter than the analysis period in which these treatments are considered. In most cases where a single treatment is considered, the benefit of an alternative, or the cost-effectiveness of a treatment, is calculated based on the additional life expected from the application of the treatment. The use of subsequent treatments allows you to consider the additional benefit realized by applying the second treatment, which more closely represents the analysis period.

Some agencies use subsequent treatments as a way to represent a phased construction project that is designed to be constructed in stages. For example, if a highway section has been scheduled for a 4 inch overlay but money is not available for its construction, the agency may elect to place 2 inches in the year the rehabilitation was scheduled and the remaining 2 inches in a later year. In the pavement management system, this phased construction would be represented as subsequent treatments.

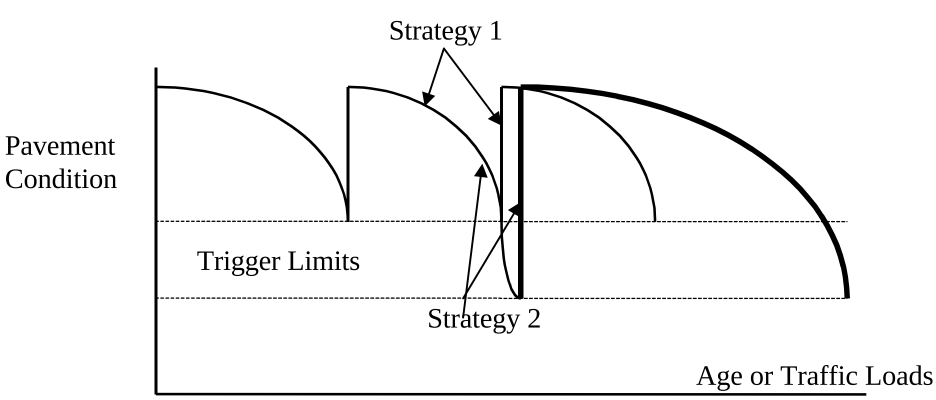
It should be noted that the subsequent treatment plays an important role in the selection of projects and treatments for the multi-year program. Both the timing and type of subsequent treatment are important for an agency to note because altering either could greatly impact the benefit or effectiveness of the entire strategy. Disregard for the subsequent treatment recommendations could have a tremendous impact on the effectiveness of the program and the long-term impacts on overall network condition.

To illustrate the concept of multiple treatment strategies, Table 10.4 and Figure 10.8 are presented. Table 10.4 provides a table that lists two treatments for four sample sections in the network. As can be seen, multiple treatments can include preventive maintenance, minor rehabilitation, or major rehabilitation actions. Figure 10.8 illustrates this concept graphically. This figure illustrates two feasible multiple treatment strategies for one pavement section; one strategy with two minor rehabilitation activities and another with a minor rehabilitation action followed by a major rehabilitation action. In determining the optimal strategy, the benefit of both treatments is considered in a benefit/cost analysis.

Table 10.4 Example of multiple treatment strategies.

Section Number	Treatment 1	Treatment 2
01	Preventive Maintenance	Minor Rehabilitation
02	Minor Rehabilitation	Minor Rehabilitation
03	Minor Rehabilitation	Major Rehabilitation
04	Major Rehabilitation	Major Rehabilitation

Figure 10.8 Multiple treatment strategies.



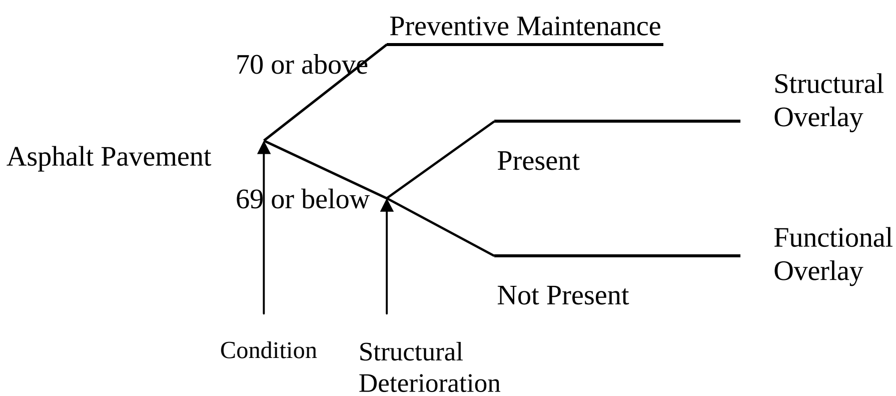
Tools Used to Develop Strategies: In order to develop strategies for the multi-year programs, it is imperative that the agency first establish:

- a list of all treatments that should be considered in the analysis, and
- the set of rules that determine when each of the treatments should be considered feasible.

There are a number of tools that are used by highway agencies to assist with these activities. These tools include decision trees, decision matrices, and programmed rules. Each of these tools is discussed further in the following sections.

Decision Trees: Decision trees establish the set of rules for selecting a particular type of treatment through the use of "branches" which define various sets of conditions. The user continues along the branches which best represent the conditions for the pavement section being analyzed until a particular treatment or choice of treatments is presented. An example of a portion of a very simple decision tree is shown in Figure 10.9.

Figure 10.9 A simple decision tree.



In most situations, the decision trees are much more complex than the one illustrated above. The state of Minnesota uses automated decision trees as one of its strategy selection tools, as discussed in the Minnesota case study. Minnesota's decision trees incorporate factors such as surface type, individual distress types present, and at least two condition ratings. The decision trees are detailed enough to identify one or two feasible treatments from a total of 58 possible treatments for each pavement section.

The development of decision trees is fairly easy for state agencies because they often replicate the thought process of the manual treatment selection process. The level of detail required for a decision tree, and the data used to form the branches, must be agency specific in order to be of use.

Although the specific data elements to be used in the decision trees are dependent on the requirements of the agency, there are some general types of data that are normally included in the development of the decision trees. These include the following:

- Pavement surface type or construction history
- An indication of functional classification and/or traffic
- At least one type of condition index, including distress and/or roughness
- More specific information about the type of deterioration present, either in terms of an amount of load-related deterioration or the presence of a particular distress type.

- Geometrics, in order to indicate whether pavement widening or shoulder repair will also be required in conjunction with the rehabilitation.

As discussed earlier, decision trees are a common tool used for treatment selection because of the similarity to the decision process normally used by an agency. This is one of its primary advantages. Other advantages include the flexibility to incorporate change and the ease with which the treatment selection process can be explained. Decision trees are also relatively easy to program so they can easily be automated and incorporated into a pavement management system.

Perhaps the primary disadvantage to the use of decision trees is the rigidity with which the rules are set. In most cases, decision trees lead to one or two possible treatments, although other less familiar treatments may be viable alternatives. Consideration is not given to the effectiveness of one treatment over another or the benefit of one treatment over another. Rather, because of the existing or forecasted conditions, a set treatment path is followed. While this may be the way business is done in most agencies, it is hard to evaluate other options that may improve the effectiveness of the decisions made within the organization.

Another disadvantage to this approach is that in order to be applicable for multi-year program development, each of the data elements used in the decision tree must be able to be predicted from the first year in the analysis in order to properly represent conditions in future analysis years. This is important because some treatments are recommended five years after the start of the analysis. If certain criteria are not forecasted, it is impossible to accurately follow the decision tree paths.

To illustrate this point, image a pavement section with a condition rating of 77 with no structural deterioration showing. As the multi-year analysis is conducted, the future condition of the pavement section must be projected into each of the analysis years. If, for example, the presence of structural deterioration is not also projected, the pavement section will never be considered for a structural overlay. Instead, it will be triggered for a functional overlay until the predicted condition falls below the allowable range. Without the projection of structural deterioration, the presence of structural deterioration can not be identified without conducting another condition survey.

Matrices: Decision matrices are very similar to decision trees except the information is presented in the form of a table, or matrix, rather than a tree. In most cases, the table is followed from left to right. The far left column normally lists the treatment to be considered and the columns to the right specify the conditions under which the treatment is recommended. Few matrices result in more than one treatment being recommended for a section. An example of a matrix, using the same information presented under the section on decision trees, is presented in Table 10.5.

Table 10.5 A simple decision matrix.

Treatment Type	Surface Type	Condition Level	Structural Deterioration
Preventive Maintenance	Asphalt Concrete	70-100	N/A
Functional Overlay	Asphalt Concrete	0-69	Not present
Structural Overlay	Asphalt Concrete	0-69	Present

As with decision trees, decision matrices can also become quite complicated. In some cases, where there are multiple criteria when a particular treatment is considered feasible, each particular treatment could have several lines in the matrix. This point is illustrated in Table 10.6 which features a portion of a matrix developed for the North Dakota Department of Transportation (NDDOT) (*4*).

Table 10.6 Decision matrix from North Dakota DOT.

Treatment	Committed Components		Surface Components		Operational Components				
	Distress	Surface Type	Struct Cond	Ride	Funct Class	ESAL	Width	Thick	ADT
	0-100	Type	0-54	0-5	Type	Range			
Thin O/L (<= 2.5 inches)	65-85	AC	15-35	Any	Any	0-74	>=27'	Any	<=750
Thin O/L (<= 2.5 inches)	70-85	AC	15-30	Any	Any	0-74	>=33'	Any	751-2000
Thin O/L (<= 2.5 inches)	70-85	AC	15-30	Any	Any	0-74	>=39'	Any	>= 2001
Thin O/L (<= 2.5 inches)	65-85	AC	15-25	Any	Any	75-100	>=27'	Any	<=750
Thin O/L (<= 2.5 inches)	70-85	AC	15-25	Any	Any	75-100	>=33'	Any	751-2000
Thin O/L (<= 2.5 inches)	70-85	AC	15-25	Any	Any	75-100	>=39'	Any	>= 2001
Thin O/L (<= 2.5 inches)	0-99	AC		< 2.5			>=39'		>= 2001

In this instance, a thin overlay could be selected for a pavement section if the criteria in line 1, or line 2, or line 3, and so on, are met. For example, using the last line in the matrix, a thin overlay would be selected for a pavement that had a ride index below 2.5 if the width was greater than 39 feet and the ADT was higher than 2001.

Decision matrices rely on the same types of information used in the development of decision trees. The particular data elements to be used are dependent on the unique decision process used by the agency developing the matrices. However, as presented earlier, there are several general types of data that are normally included in decision matrices. This information is replicated from the section on decision trees.

-

- Pavement surface type or construction history
- An indication of functional classification and/or traffic
- At least one type of condition index, including distress and/or roughness
- More specific information about the type of deterioration present, either in terms of an amount of load-related deterioration or the presence of a particular distress type.
- Geometrics, in order to indicate whether pavement widening or shoulder repair will also be required in conjunction with the rehabilitation.

Because of the similarities between decision trees and decision matrices, the advantages and disadvantages are also similar. In some cases, decision matrices can be more confusing to follow manually than decision trees because the matrix generally starts with the rehabilitation treatment and the user must find the criteria used to select that treatment. A decision tree, on the other hand, generally outlines the specific conditions that must be met so the user is led to the treatment recommendation. The decision matrix is probably slightly easier to program than the decision tree.

Programmed Rules: Some agencies prefer to establish a fairly simplistic set of rules that are followed in order to identify the preferred treatment type. In general, these rules identify only a few criteria that must be met to select the preferred treatment. An example of a rule was presented earlier when it was established that minor rehabilitation is applied between a condition range of 75-90 and a thin overlay is recommended for a condition between 65 and 80 when no structural deterioration is present. It is fairly simple to transfer rules into either decision matrices or decision trees.

Types of Treatments Considered in Strategy Development: A number of different types of treatments can also be considered in the strategy development process. In general, agencies prefer one of two approaches:

- a category of rehabilitation is recommended or
- a specific type of treatment is recommended.

Both of these approaches are discussed further in the following sections.

Rehabilitation Categories: Some agencies feel that a pavement management system should not be used at the network level to make recommendations for specific types of treatments. Instead, these agencies choose to identify treatment categories, such as routine maintenance or minor rehabilitation. Within each of these categories, a number of feasible treatments are normally identified. For example, the category routine maintenance may include crack sealing, joint filling, or the application of a seal coat. Once the routine maintenance category has been identified, the agency conducts a more in-depth investigation as to the specific type of treatment necessary. Typical rehabilitation categories are listed below.

- Maintenance
- Minor rehabilitation
- Major rehabilitation
- Reconstruction

One disadvantage to this approach is that fairly general cost data and performance models must be used within the pavement management system when this approach is used. Instead of recommending crack sealing or a seal coat for a particular section, each of which has specific costs associated with it, the pavement management system must estimate an average cost associated with routine maintenance. This average cost is then used to allocate the available budget. Any improvements that can be made to estimating costs obviously benefit the entire process.

The same holds true with forecasting future conditions. If general categories are used, they are also used for developing deterioration models. This may result in very generic models that do not adequately represent the different deterioration patterns of specific types of treatments. Some agencies have overcome this limitation by adding a function that allows the pavement performance model to *shift* in accordance to the performance of each individual section. In this way, pavement sections that are performing better than the average condition can be treated differently than sections performing far worse than the average.

Specific Treatments: Other agencies prefer using their pavement management system to identify feasible treatments that are further developed as part of a project scoping meeting. NCHRP Synthesis 222, *Pavement Management Methodologies to Select Projects and Recommend Preservation Treatments* (*3*), queried state highway agencies about their project and treatment selection process. One of the questions concerned the types of treatments that were considered in a PMS. The treatments listed in Table 10.7 were the most commonly considered treatments for pavement preservation projects.

Table 10.7 Most common treatments used in strategy development.

Asphalt	Concrete
Routine maintenance	Slab grinding
Surface seal coats	Full- and partial-depth repairs
Milling and inlays	Crack and seat
Thin overlay	Thin-bonded overlay
Thick overlay	Unbonded overlay
Mill and overlay	Micro-surface overlay
Reconstruction	Slab replacement
	Reconstruction

Agencies using this approach feel that the treatment recommendations provide better estimates of the type of treatment that will be necessary to address the pavement deficiencies and that initial cost estimates better reflect actual agency costs.

One disadvantage to this approach is that the agency must develop performance models, cost information, and decision trees/matrices for each of the treatments considered in the program. For this reason, many agencies limit the number of treatments considered in their analysis.

Perhaps the largest disadvantage is that limited information is used to identify the feasible rehabilitation treatments for each section. This disadvantage can be eliminated, or diminished, by providing as much information as possible about the pavement section.

APPLICATIONS OF STRATEGY DEVELOPMENT TO MULTI-YEAR PRIORITIZATION: There are a number of states that provide excellent examples of the strategy development process. The state of Indiana provides an excellent example of a state that uses a multiple strategy approach to treatment selection. Each treatment is defined in terms of an initial treatment and a subsequent treatment that is triggered at a set condition level. Costs, performance models, and trigger levels are defined for each feasible treatment type. Indiana enters the trigger levels for each treatment into a treatment matrix.

Minnesota provided the best example of a set of decision trees for identifying the most appropriate rehabilitation strategy. As discussed earlier, these decision trees include a total of 58 types of maintenance and rehabilitation, triggered primarily by condition levels, functional classification, and the particular distress present.

The state of Illinois has a fixed set of rules that are followed for the identification of the appropriate type of treatment. In this example, only a few treatments are considered and very specific conditions exist for determining when each treatment is applied. For example, the state's SMART program is designed only for pavements in a very high condition range.

Many other states have developed tools that are effective in the strategy development process. The state of North Dakota is an excellent example of a state where decision matrices have been developed to carefully identify all conditions for which a particular treatment is considered feasible. As shown in the sample matrix presented earlier, the North Dakota matrices are very intricate.

10.4 Prioritization Techniques

In MYP, the recommended projects and associated treatments are identified through the use of a prioritization analysis that identifies the costs associated with each strategy and the improvement (or effectiveness) that each possible strategy provides to the network.

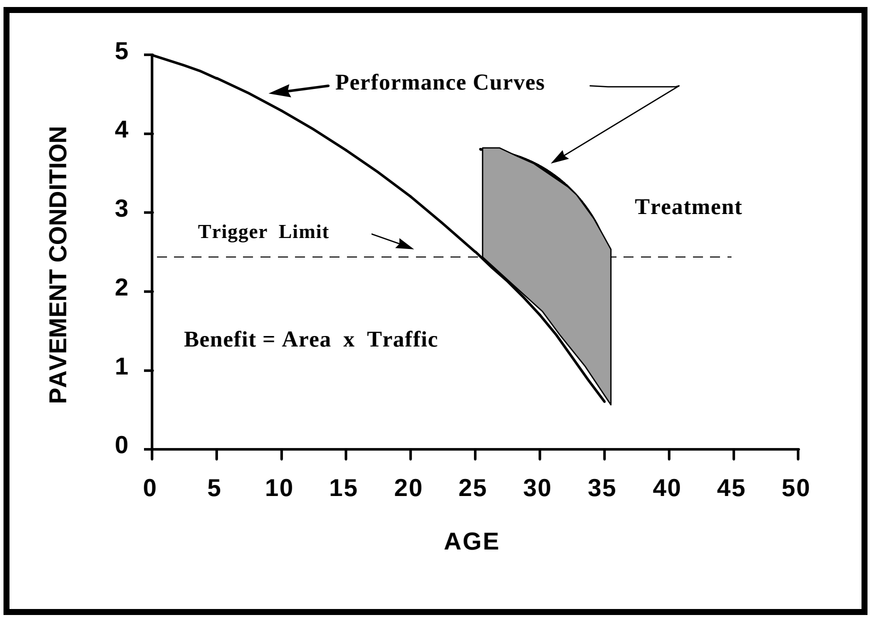
An effective analysis tool for prioritizing and selecting projects should consider the following seven principles (*5*).

- The management level at which the evaluation is to be made must be clearly identified.
- The economic analysis provides the basis for a management decision but does not by itself represent a decision.
- Criteria, rules, or guides for such decisions must be separately formulated before the results of the economic evaluation are applied, even though such criteria may be straight forward and simple.
- The economic evaluation itself has no relationship to the method or source of financing a project.
- An economic evaluation should consider all possible alternatives, within the constraints of time and other planning and design resources.
- All alternatives should be compared over the same time period.
- The economic evaluation of pavements should include agency costs and user costs and benefits if possible.

In a multi-year prioritization analysis, there are two primary components. First, the analysis must provide a way of determining the benefit, or effectiveness, provided by the application of the treatment. In addition, the analysis must provide a way to estimate the total costs associated with each treatment. Together, this information provides the information necessary to compare the effectiveness of one treatment to another per unit cost.

Effectiveness or Benefits: Each possible treatment or rehabilitation strategy provides some additional life to the pavement section through its application. In a MYP analysis, this additional life is referred to as the effectiveness or benefit provided by the treatment. Effectiveness is always calculated in non-monetary terms. This is normally done by taking the area under a curve and multiplying it by some traffic factor. The curve is usually some type of condition indicator such as Pavement Quality Index (PQI) or Pavement Condition Index (PCI). Benefits, on the other hand, can be either monetary or non-monetary. As with user costs, monetary benefits are difficult to calculate with a reasonable degree of accuracy. For this reason, most agencies estimate benefits in the same manner effectiveness is estimated; as the area under a condition index curve times a traffic factor. The area under the condition curve is best understood by a graph as shown in Figure 10.10.

Figure 10.10 **Calculation of benefit. In most cases, the area under the curve is multiplied by traffic to determine the total benefit.**



Cost: Life-cycle cost analysis (LCCA) includes the evaluation of agency, user, salvage, maintenance, and other relevant costs over the life of investment alternatives. At the network level, life-cycle costs are used for each feasible treatment or strategy to determine the total costs that will be incurred over the estimated life of the alternative.

Present Worth (PW) and Equivalent Uniform Annual Cost (EUAC) are the most common methods used at the network level for life-cycle cost estimates. Due to the difficulty in assigning life-cycle costs at the network level, several agencies rely on initial costs, an estimate of annual maintenance costs, and a discount rate as the principal factors used in the LCCA.

Prioritization Analysis Techniques: There are two commonly used approaches for performing a multi-year prioritization analysis: marginal cost-effectiveness analysis and incremental benefit/cost analysis. Each of the analysis techniques generates a ratio as a means of determining which strategies are the most cost-effective. A ratio greater than or equal to one is consider a viable strategy when a ratio of less than one is considered to be a costly strategy. The better the estimates of benefit and cost for each treatment (or strategy), the better the ratio is able to illustrate the relative cost-effectiveness of one treatment over another. Each of these techniques is discussed further in the following sections.

Marginal Cost-Effectiveness Approach: The Marginal Cost-Effectiveness (MCE) approach is a method of assessing the cost-effectiveness of a particular project and its associated treatment through the use of an effectiveness ratio. By comparing the ratio of one strategy to another, the most cost-effective projects for the network can be identified for the funding levels available.

The following steps are completed in the marginal cost-effectiveness analysis:

- Identify the feasible treatments for each analysis period based on the projected condition and established trigger levels;
- Calculate the effectiveness (E) of each combination of strategies (effectiveness is generally the area under the performance curve multiplied by some function of traffic);
- Calculate the cost (C) of each combination in net present value terms.
- Calculate the cost-effectiveness (CE) of each combination as the ratio of E/C, where the highest value is the best.
- Select the treatment alternative and time for each section with the best CE.
- Calculate the marginal cost-effectiveness (MCE) of all other strategies for all sections as follows:

$$MCE = (E_r - E_s)/(C_r - C_s)$$

where:
E_s = effectiveness of the strategy selected in step 5
E_r = effectiveness of the strategy for comparison
C_s = cost of the strategy selected in step 5
C_r = cost of the strategy for comparison

- If the MCE is negative, or if E_r is less than E_s, the comparative strategy is eliminated from further consideration; if not, it replaces the strategy selected in 5.
- This process is repeated until no further selections can be made in any year of the analysis period.

This type of approach has been shown to give near optimum results (Lytton 1994). The following example of a simple MCE analysis was provided by the Minnesota Department of Transportation (MnDOT). The analysis is based on a network with three sections (segments A, B, and C) and a budget level of 11. The following steps summarize the MCE analysis.

Table 10.8 Results of a cost-effectiveness analysis.

SEG	ALT	Treatment	Eff.	Cost	CE	MCE's					FINAL
A	1	Seal Coat	1	1	(1/1) = 1.0	1	***	***	***	***	
	2	1" Overlay	5	2	(5/2) = 2.5	2.5	Use	Use	***	***	
	3	2" Overlay	8	4	(8/4) = 2.0	2	1.5	1.5	Use	Use	Use
	4	4" Overlay	11	8	(11/8) = 1.4	1.4	1	1	0.8	0.8	
B	1	2" Overlay	8	4	(8/4) = 2	2	2	Use	Use	***	
	2	3" Overlay	10	6	(10/6) = 1.7	1.7	1.7	1	1	Use	Use
	3	4" Overlay	11	8	(11/8) = 1.4	1.4	1.4	0.8	0.8	0.5	
C	1	Joint Seal	3	1	(3/1) = 3	Use	Use	Use	Use	Use	Use
	2	Joint Repair	5	4	(5/4) = 1.2	0.7	0.7	0.7	0.7	0.7	
	3	3" Overlay	10	6	(10/6) = 1.7	1.4	1.4	1.4	1.4	***	
				Budget	12	11	9	5	3	1	

Step 1: Calculate the cost-effectiveness (CE) of each treatment. Identify the strategy with the highest CE and determine the marginal cost-effectiveness (MCE) increase provided by other strategies for that section.

The highest CE is associated with Alt. C1, joint seal, with a CE of 3.0. The MCE provided by the other two feasible strategies for segment C can be calculated as shown below.

MCE for Alt. C2 = (Effectiveness of C2 - Effectiveness of C1)/(Cost of C2 - Cost of C1)

MCE for Alt. C2 = (5-3)/(4-1) = 2/3 = 0.7

Similarly, the MCE for Alt. C3 can be calculated in a similar fashion.

MCE for Alt. C3 = (10-3)/(5-1) = 7/4 = 1.4

Step 2: Update the Effectiveness Table using the MCE for Alts. C2 and C3.

The MCE then replaces the CE considered for alternatives C2 and C3 because only the marginal amount of cost effectiveness over the selected strategy for segment C should be considered further.

Step 3: Determine the remaining budget.

The available budget was 12, but we used 1 for Alt. C1. The remaining budget then is 12-1 = 11.

Step 4: Find the highest CE or MCE from the revised table developed in Step 2. Determine the MCEs for any other feasible strategies for the segment selected.

From the table shown after Step 2, it is clear that the next highest CE or MCE is associated with Alt. A2 (2.5). The MCEs for the other strategies associated with Segment A must be calculated.

MCE for Alt. A1 = (1-5)/(1-2) < 0. Since there is less marginal effectiveness associated with this treatment, it is no longer considered in the analysis.

MCE for Alt. A3 = (8-5)/(4-2) = 3/2 = 1.5

MCE for Alt. A4 = (11-5)/(8-2) = 6/6 = 1

Step 5: Update the Effectiveness Table and the Budget.

The remaining budget is 11-2 = 9

Step 6: Repeat the selection of the highest CE or MCE, and calculate MCEs for any other treatments from the selected segment.

Using the table from step 5, the highest CE or MCE is the 2.0 associated with Alt. B1. The calculation of the MCEs from Alt. B2 and Alt. B3 is shown below.

MCE for Alt. B2 = (10-8)/(6-4) = 2/2 = 1.0

MCE for Alt. B3 = (11-8)/(8-4) = 3/4 = 0.8

Step 7: Update the Effectiveness Table and the remaining budget.

The remaining budget is 9-4 = 5

Step 8: Repeat the selection of the highest CE or MCE and calculate any MCEs for remaining strategies for the selected section.

Using the table shown above, Alt. A3 has the highest MCE associated with it (1.5). It is now selected in place of Alt. A2. because the available budget allowed the selection of an alternative with a higher marginal cost effectiveness than the original choice would have provided.

The MCE for Alt. A4 is calculated as: (11-8)/(8-4) = 3/4 = 0.8

Step 9: Update the Effectiveness Table and Calculate the remaining budget.

The remaining budget is 5+2(from Alt. A2) - 4(from Alt. A3) = 3

Step 10: Repeat the selection of the highest MCE for the available funds and re-calculate any MCEs.

Using the table shown above, Alt. C3 has the highest MCE of any of the other alternatives. The remaining budget of 3, however, prevents us from selecting this alternative which has a cost of 6 associated with it (even after the cost of Alt. C1 is added back in). Returning to the table, the next highest MCE is associated with Alt. B2. Which has an acceptable cost associated with it after the cost of alt. B1 is added back to the budget.

MCE of Alt. B3 = (11-10)/(8-6) = 1/2 = 0.5

Step 11: Update the Effectiveness Table and the Remaining budget.

The remaining budget = 3+4(Alt.B1) - 6(Alt. B2) = 1

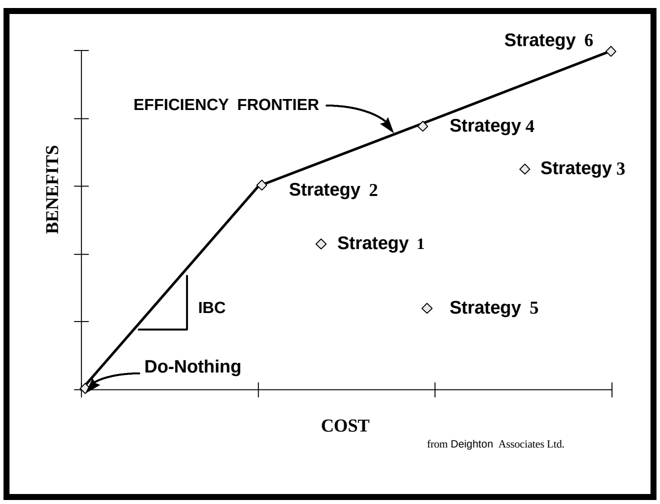
Step 12: In order of MCEs, determine whether the remaining budget will allow any of the remaining alternatives to be selected. If so, calculate MCEs, update the Effectiveness Table, and calculate the remaining budget. If not, end the analysis.

The remaining budget of 1 does not allow Alt. B3, Alt. A4, or Alt.C2 to be considered further. The final selection of treatments, the overall effectiveness, overall cost, and overall cost effectiveness of the selected program is shown below.

The overall effectiveness of the selected program is (8+10+3) = 21. The overall cost is (4+6+1) = 11. Based on that information, the overall CE for the program is 21/11 = 1.9. For the budget level allowed, this is the most cost-effective program that could have been selected. If additional funds had been made available, a more cost effective program could have been determined.

Incremental Benefit/Cost Approach: Incremental benefit/cost (IBC) is another approach used to evaluate the cost- effectiveness of different combinations of projects. The IBC approach is very similar to the MCE approach except that benefits are used rather than effectiveness in the analysis. In most cases, the calculation of the benefit as the area under the curve is the same as the measure of effectiveness. To calculate benefit, the area may, or may not, be multiplied by some measure of traffic. The selection of the optimal combination of projects and treatments in an IBC analysis is illustrated through the use of an efficiency frontier, as shown in Figure 10.11 (*8*). The seven dots on the graph each represent the costs and benefits associated with seven strategies; a do-nothing and six repair strategies labeled 1 through 6. The upper most dots are joined together with a segmented line.

Figure 10.11 Incremental benefit/cost efficiency frontier.



Each line segment was drawn by starting at the do-nothing point and drawing the segments in such a way that no strategy points exist above the line, and no line segment has a bigger slope than the previous line segment. This segmented line is called the ‘efficiency frontier’.

The slope of each successive line segment is called the incremental benefit cost of going from one strategy to the next. Strategies which fall on the efficiency frontier provide the most benefit per unit cost for the agency.

In order to conduct an IBC analysis, both costs and benefits are expressed in terms of Equivalent Uniform Annual Costs (Benefits) (EUAC or EUAB). This conversion translates all initial and future costs into an equivalent uniform annual cost rather than a one-time present worth cost so that all strategies can be compared on an equal basis even though treatments are scheduled at different points during the analysis period.

The incremental benefit/cost analysis techniques are well documented in the literature (*7*). The first step in the analysis is the calculation of the equivalent uniform annual cost (EUAC) and equivalent uniform annual benefit (EUAB) associated with each rehabilitation strategy.

The following equation is used to calculate the EUAC.

$$\boxed{EUAC = PVC * \frac{(r*(1+r)^n)}{((1+r)^n - 1)}}$$

where: PVC = Present Value Cost

r = Discount Rate

n = Number of Years

The following equation is used to calculate the EUAB for each strategy.

$$\boxed{EUAB = PVB * \frac{(r*(1+r)^n)}{((1+r)^n - 1)}}$$

Th EUAB is divided by the EUAC to determine the benefit/cost ratio associated with each treatment (or strategy). The incremental benefit/cost (IBC) of the strategies are calculated using the following equation.

$$\boxed{IBC_j = \frac{(EUAB_j - EUAB_{j-1})}{(EUAC_j - EUAC_{j-1})}}$$

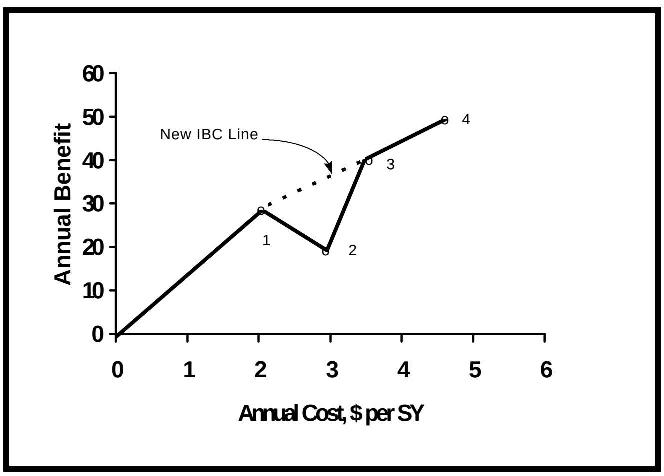
The strategies for each section are then sorted in increasing order of IBC and any negative IBCs (indicating no additional incremental benefit) are eliminated from consideration. The use of IBC is a near optimization approach that selects the best strategy for each road section to maximize benefits without exceeding budget levels.

Table 10.9 illustrates the IBC approach for a single feature (*7*). The data are shown graphically in Figure 10.12. The IBC is defined as the ratio between the increase in benefit to the increase in cost between successive M&R alternatives (where M&R alternatives are arranged in an increasing order of EUAC per square yard). As shown in Figure 10.12, alternative 2 is eliminated since it shows an increase in cost and decrease in benefit. The selection of alternatives 1, 3, or 4 is a function of available budget. Alternative 1 provides the highest ratio of benefit to cost; however, alternative 4 provides the maximum benefit if funding is available.

Table 10.9 Calculation of benefit/cost ratios.

Feature No.	M&R Alternative Number	Initial Cost (Dollars)	EUAC (Dollars per Square Yard)	Annual Benefit	Benefit/Cost Ratio
1	1	24,000	2.10	32	15.2
	2	32,000	2.80	28	10.0
	3	37,000	3.20	45	14.1
	4	47,000	4.10	53	12.9

Figure 10.12 Annual benefit vs. annual cost.



10.5 Project Selection Process

Multi-year prioritization is a tool used by SHAs to assist in determining the most cost-effective combination of projects, treatments, and timing of pavement rehabilitation activities. The recommendation from the PMS, however, can not be implemented in isolation of other needs that must be addressed by the SHA. Those other needs that must be considered include bridge improvements, safety improvements, and capacity enhancements, among others. Other factors, such as a road improvements required to address upcoming commercial developments or the need to combine projects in similar geographical proximity to one another in order to obtain more competitive construction prices must also be considered.

Because of these types of factors, the final selection of projects and treatments must be done in cooperation with other Offices or Divisions within the highway agency. The results of the multi-year prioritization are an important part of this process, enabling the agency to evaluate trade-offs between various options through the information this type of analysis provides.

The project selection process consists of a series of engineering and planning activities that assist decision makers in developing the multi-year highway improvement program that address the goals of the organization and deficiencies in the network. This process integrates the operation and preservation of the existing highway network with the long-term transportation development and performance objectives for the highway network. It is often an iterative process that involves an on-going assessment of the trade-offs between each alternative considered. Most highway agencies have their own distinctive project selection process.

Project Selection Activities: Although the project selection process varies from state to state, there are a number of activities that are normally undertaken to help decision-makers identify, evaluate, and select the projects to be included in the highway improvement program. Depending on the organizational structure of the highway agency, the activities may be conducted by Central Office or District engineers. The most common project selection activities are:

- Network Needs Assessment.
- Scoping Reviews.
- Evaluation of Inter-Project Trade-offs
- Investment Analysis

Network Needs Assessment: Before the project selection process can begin, project needs must be identified through the use of existing management systems or departmental recommendations. These recommendations, which include bridge projects, pavement improvements, safety, and capacity enhancements, must be evaluated to determine a list of network needs.

The purpose of this assessment is to identify sections of the network that were identified as the highest candidates for rehabilitation in terms of pavements, bridges, safety features, capacity, etc. During this process, a team of engineers use information provided by different offices within the agency to evaluate the condition of different sections of the network and combine the different needs to form potential projects.

Detailed Project Scoping Reviews: Project scoping reviews involve site visits intended to identify all the work items needed to improve the projects that have been identified in the previous activity. Scoping reviews can be conducted by district personnel or may involve representatives from throughout the agency, including districts, planning, design, bridges, and maintenance.

Evaluation of Inter-Project Trade-offs: All the improvement needs are evaluated and prioritized in order of importance for each individual project or section of the network. Some improvement needs are combined in one project or deferred to a more appropriate time or funding scenario.

Investment Analysis: The estimated costs to improve each component of the highway program (interstate routes, bridges, traffic & safety, local programs, etc.) are analyzed to determine present and future budget needs. The budget needs are compared with expected revenues and funding allocations from Federal, State and Local Agencies to establish the improvement program that best meets the agency's goals and objectives.

Integration of Pavement Management Into Project Selection Process: The information from a multi-year prioritization analysis is an important part of the project selection process. The activities and information produced by the PMS helps decision-makers to:

- Determine the overall condition of the highway network.
- Select cost-effective pavement preservation treatments.
- Evaluate the effectiveness of different preservation strategies in the overall condition of the network.
- Evaluate the effect of different budget scenarios in the network condition.
- Determine budget needs and set budget limits.

The PMS Office can be instrumental in coordinating a number of efforts between different divisions within the highway agency. The following examples illustrate this point.

- In one state agency, the Pavement Management Section works with the Pavement Design Committee to analyze different rehabilitation strategies, such as whether multiple thin overlays can be applied, or what strategy should be considered after a crack and seat is performed. These types of decisions become important as the Pavement Management Section analyzes feasible rehabilitation strategies as part of its multi-year prioritization process.
- In another agency, the prioritized list of pavement preservation projects is used as the basis for determining all feasible project sites to be reviewed by the field scoping committee. After the committee reviews each site, scopes for each project are prepared. These scopes describe the improvement and budget needs for each project. Based on the information from the scoping visits, the projects are re-prioritized and the PMS list is used to record the final projects and provide the information to the rest of the SHA.

One benefit of integrating the MYP analysis results into the project selection process is that the efficiency of the pre-construction process is often greatly improved. Some agencies have also seen improved coordination between the efforts of various divisions and districts. As a result, there is generally a better understanding of the projects selected for the program and fewer changes required once a project is programmed.

10.6 Case Studies

There are a number of excellent examples of state highway agencies using a MYP analysis. A case study from one such agency, the Indiana DOT (InDOT) is provided (*1*).

InDOT uses a multi-year prioritization process to establish feasible rehabilitation projects for the interstates within the state. They are currently developing the same process for their principal arterial highways. To date, one complete programming cycle has been developed using the new software and procedures in place within the Department. Although the first use of these processes took a number of months, InDOT expects that the current and future cycles can be done more efficiently as people become more familiar with the changes.

An Overview of the Analysis Process: InDOT utilizes a database that resides on a mainframe computer to store roadway inventory information from locations throughout the state. Relevant information for the identification of rehabilitation projects and treatments is downloaded into the dROAD database, that resides on a personal computer in the Pavement Management Section. The information contained in dROAD is then used to update pavement deterioration models, and other models used in the pavement management analysis.

Based on current and forecasted condition levels, an incremental benefit/cost routine is used to prioritize all feasible rehabilitation projects over a 5-year window. The analysis is generally run for a 5-year period beginning 2 years from the year in which the analysis is initiated, due to the large number of projects already in the programming and design stages for the earlier years.

The prioritized candidate project list, which includes proposed levels of rehabilitation, are then used as a *first cut list* to be evaluated further. A scoping committee, made up of individuals from Roadway Management, Bridges, Preliminary Engineering, Design/Materials, Districts, and FHWA visit each of the sites to examine the existing conditions and identify any variations or other factors that may affect the project. A field evaluation packet is brought out to the field to facilitate the field decisions. As a result of the site visits, mini scopes are developed for each candidate project so cost estimates can be improved, and new priorities are established for each of the years in the analysis. As the list is revised, the committee meets periodically to review the priorities and make final changes to the program. When a final program is approved by the committee, it is put into the programming pipeline and projects are then let for design. The following is the step-by-step interstate planning process use by InDOT PMS.

Step 1. Collect condition data.

Step 2. Load and analyzed data using the PMS software.

Step 3. PMS software identify proposed new projects.

Step 4. Scoping team field check and review projects. Project limits are modified. Project priorities are reset and rehabilitation alternatives are selected.

Step 5. Intended scope is documented with cost estimate and alternatives for each project.

Step 6. Projects are combine and re-analyze using the PMS software.

Step 7. Proposed projects are included in the five year program if their cost satisfy the establish budget limit.

Step 8. If project cost does not satisfy the budget, there are two options: Revised the scope, cost and documentation. If so, revise the project and go back through Step 6. Otherwise, keep project scope and include the project in the long term program.

Analysis Tools: In order to generate a multi-year prioritized list of candidate projects for the interstate, a number of analysis tools must be defined and developed within the dROAD and dTIMS software programs. The development of these tools was done almost exclusively by the Pavement Management Section over a 2-year period.

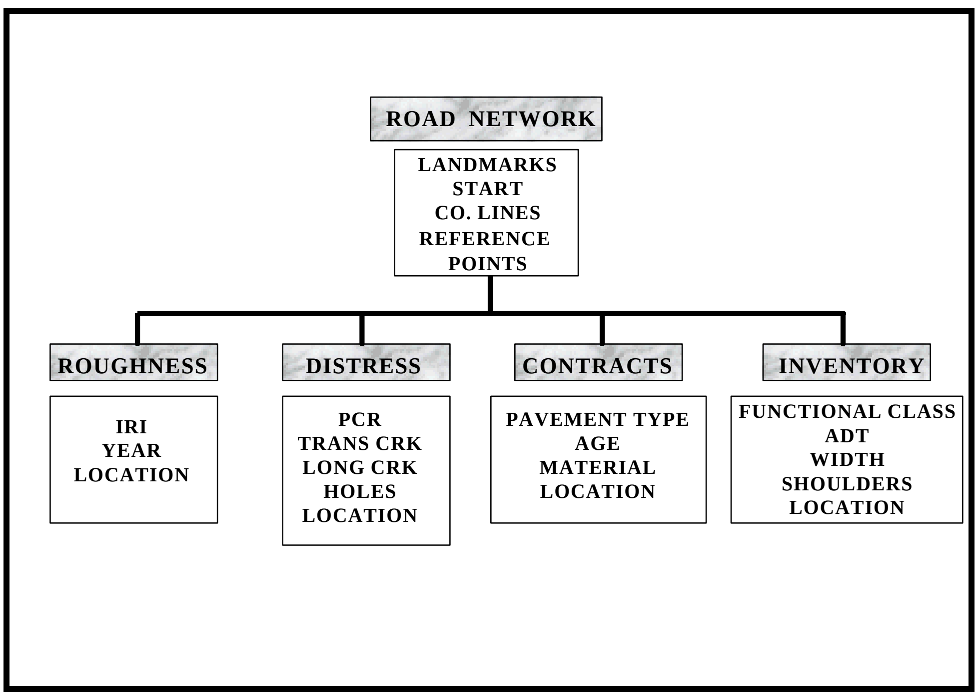
Software Tools: A number of programs are used as part of the analysis. First, the majority of data for the roadway system resides on the Department's mainframe computer.

Pavement related information is downloaded from the mainframe into the dROAD program that resides on the personal computer in the Pavement Management Section.

dTIMS, which also resides on the personal computer in the Pavement Management Section, is used as the analysis tool for the pavement management process. It uses data provided through dROAD to generate the multi-year prioritized lists of candidate rehabilitation projects. As the project list is finalized and the required budgets for each project are determined, this information can be input into dTIMS and new priorities can be established.

Required Data: The information about the pavement network must be available in order to perform a multi-year analysis. In very general terms, any information used in the decision process to recommend projects and/or their associated treatments must be included. This type of information includes, but is not limited to, general referencing information, distress, roughness, and rutting information, pavement history related data, and inventory type data as shown in Figure 10.13. This information is used by the analysis tools explained in the next section to perform the required analysis over the multi-year period.

Figure 10.13 Basic data used in Indiana's multi-year prioritization analysis.



Analysis Groups: The pavement management analysis requires that several tools be developed in order to generate the multi-year list of projects. First, analysis groups are established. These analysis groups define pavements with like characteristics, such as pavements with the same functional class, traffic volumes, or pavement type. The groups can be used to establish performance models or to run different analysis conditions.

Performance Measures: In order to develop multi-year programs, the analysis program must contain tools for establishing current and future condition levels. A number of different approaches can be used to establish measures of pavement condition, including distress, rutting, ride, d-cracking, and structural deficiencies. Some agencies prefer to use a combination of these condition indicators through the use of some type of composite condition index. InDOT used both individual condition indices and combined indices as part of their project selection process.

In order to identify the current pavement condition of their network, IDOT records and reports ride, rutting, and distress information. Individual condition indices are developed for each type of information, as discussed earlier. As a result, the following indices are calculated:

- Pavement serviceability index (PSI) for ride.
- Pavement condition rating (PCR) for distress.
- Rut index (RUT) for rutting.

These three indices are used to report network conditions throughout the Department and also serve as the basis for identifying the feasibility of different rehabilitation strategies in the decision matrices. The three indices are also used to calculate a composite index, referred to as the Pavement Quality Index (PQI) according to the following equation for interstate composite pavements.

$$\boxed{PQI = 0.55\ PCR + 8.8\ PSI - 0.25\ RUT}$$

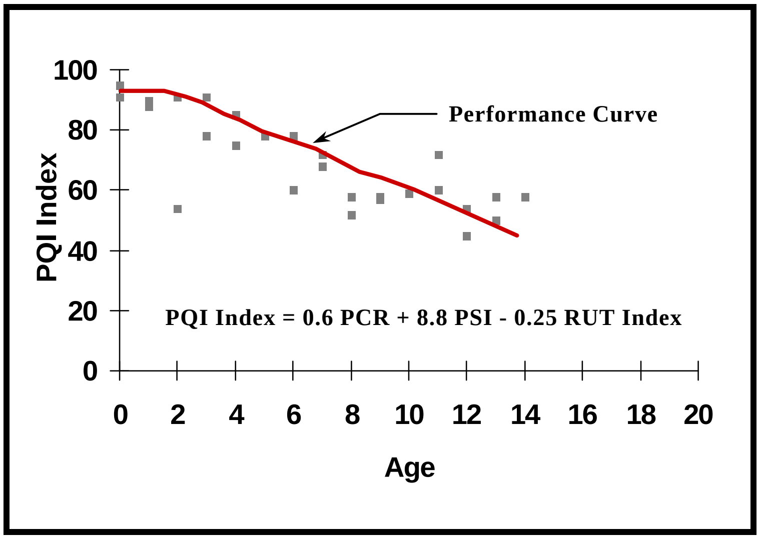
Deterioration Models: The forecasting of future network conditions can not be done without the development of deterioration models or performance curves. A number of techniques can be used for the development of these models, including mathematical programming techniques, regression analysis, or other statistical approaches. InDOT utilized a regression analysis to develop individualized performance curves for their PSI, PCR, and RUT indices. The PSI, PCR, and RUT indices graphs were added to show PQI deterioration curve. The dTIMS program produces the PQI automatically. Table 10.10 presents the performance curves completed (✔) or close to be completed (✷) within the next year.

Table 10.10 Completed performance models.

Functional Class/Surface Type	PSI	PCR	RUT	PQI
Interstate Composite	✔	✔	✔	✔
Interstate Flexible	✔	✔	✔	✷
Interstate Crack and Seat	✔	✔	✔	✷
Interstate Jointed Concrete	✔	✔		✷
Interstate Continuously Reinforced Concrete	✔	✔		✷
State Route Composite	✷	✷	✷	✷
State Route Asphalt	✷	✷	✷	✷
State Route Composite - Low Traffic	✷	✷	✷	✷
State Route Asphalt - Low Traffic	✷	✷	✷	✷
Other Jointed Concrete	✷	✷		✷
Other Continuously Reinforced Concrete	✷	✷		✷

The results of the regression analysis for the PQI deterioration model used on interstate composite pavements is shown in Figure 10.14.

Figure 10.14 A performance curve for interstate composite pavements.



Treatment Identification: Secondly, the Department had to establish the list of treatments that were to be considered as part of the analysis. At the present time, five treatments are considered for Interstate pavements, including the following:

- Mill and thin resurface (used only on asphalt pavements).
- Structural overlay (used on any surface type).
- Crack and seat and overlay (used on jointed concrete pavements).
- Replace (used on any surface type).

Note: Maintenance activities, such as crack sealing, are not listed. These maintenance activities are done using InDOT personnel on an as-needed bases.

In addition to identifying the types of treatments to be considered as part of the analysis, it was also important to identify the costs associated with each particular treatment and the *reset value*, which changes the pavement type or pavement condition when the particular treatment is applied. These reset values are used in the analysis as part of the life-cycle cost analysis. Table 10.11 lists each treatment considered by InDOT in their interstates and their associated costs.

Table 10.11 Treatments and costs considered on the Interstate.

Interstate Treatments and Cost	
Treatment Type	**Cost per sq yd**
Mill and Resurface	$6.00
Structural Overlay Rural	$50.00
Structural Overlay Urban	$60.00
Crack and Seat Rural	$50.00
Crack and Seat Urban	$60.00
Patch	$5.00
Replace Rural	$66.00
Replace Urban	$77.00

Another aspect of treatment development is the establishment of trigger levels that define when each treatment should be considered feasible for each of the various types of pavement. Additionally, the trigger levels can be used to define the level of service which needs to be maintained for each of the various pavement groupings. A number of different factors may be used to establish trigger values, including surface type, functional classification, condition levels, and types of deterioration present. At InDOT, decision matrices were developed for the trigger limits established for interstate pavements, as illustrated in Figure 10.15. These matrices are divided by surface type, then ride values, rutting ratings, and PCR values. Further enhancements to the decision matrices may be developed in the future so that multiple treatments can be considered for pavements in a given condition level.

Figure 10.15 This figure illustrates the decision matrix for composite pavements.

PVMT	COMPOSITE					
PSI	GOOD 5-3.5		FAIR 3.5-2.8		POOR < 2.8	
RUT	GOOD <0.45	BAD >0.45	GOOD <0.45	BAD >0.45	GOOD <0.45	BAD >0.45
PCR						
100-90	NO	R/S	NO	R/S	R/S	4R
90-80	NO	R/S	NO	R/S	R/S	4R
80-70	NO	R/S	R/S	4R	4R	4R
70-60	4R	4R	4R	4R	4R	4R
60-50	4R	4R	4R	4R	RPL	RPL
<50	4R	4R	RPL	RPL	RPL	RPL

Financial Parameters: The final step in developing the analysis tools is the development of budget levels anticipated in each year of the analysis. In addition, the agency may choose to input economic factors affecting the life-cycle cost analysis of the different rehabilitation strategies by entering values such as inflation or discount rates.

The Analysis Procedures: The pavement management analysis is conducted through a series of steps that are conducted automatically by the dTIMS software. These steps include the following activities.

- Shifting the performance curves to fit actual conditions.
- Triggering initial treatments.
- Calculating reset values.
- Calculating subsequent condition indices.
- Triggering subsequent treatments.
- Calculating costs.
- Calculating benefits.
- Calculating incremental benefit/cost values.
- Optimizing the selection of strategies.

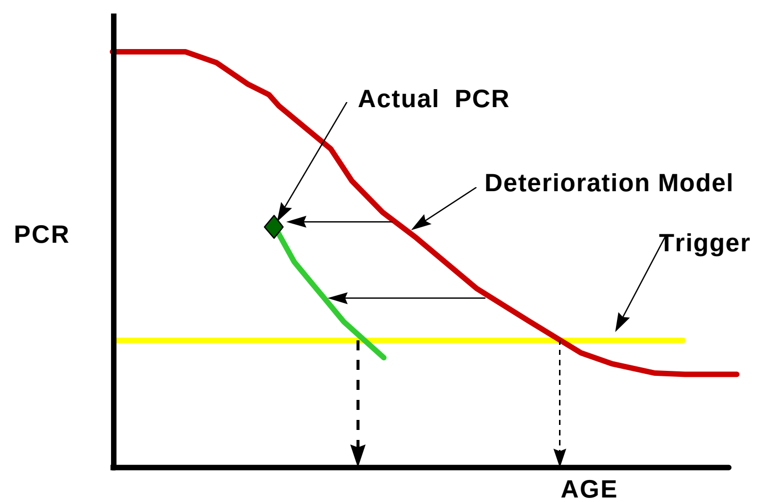
After these activities have been completed, the Pavement Management Section has a prioritized list of candidate projects and treatments that are then provided to a committee who conducts a site visit of each of the projects on the list. Based on the information obtained as part of the field visits, the projects are reprioritized, new scopes and costs are developed, and a final program list is developed.

Each of the steps in the analysis is important to ensure that the initial recommendations of the system are appropriate to the needs of the InDOT. In order to better understand these steps, each is discussed in more detail in the following sections.

Shifting the Performance Curves to Fit Actual Conditions: An earlier section illustrated the use of deterioration models for forecasting the future values of each of the condition indices used by InDOT. Since rehabilitation treatments can be triggered in any one of the five years used in the pavement management analysis at InDOT, current condition data must be used to forecast future conditions so that the analysis program knows what condition level the pavement will be in for each year in the analysis. The deterioration models developed by InDOT are representative of the overall deterioration trends of pavements with particular surface types and functional classifications, and may not match the actual values obtained for a particular pavement section's age and condition. In other words, the deterioration curve may pass through a PCR of 70 about 10 years after construction. Although this may reflect the trend for that type of pavement, there may be a section in the database that has a condition of 60 at 10 years, and another with a condition of 80 at that same point in time. Because of the variation in condition of the actual condition points, the deterioration curves must be shifted to take into account pavements that are performing better, or worse, than the general trends for that group of pavements.

The shifting of the curve is carried out automatically in dTIMS by shifting the curve through the condition/age point for each pavement section. A parallel curve is then drawn from that point on, reflecting the same overall trend as the group's curve, only shifted to the left or right depending on whether the pavement section is in better or worse condition than the trend line. For pavements deteriorating faster than the trend line, the rehabilitation triggers will be hit at an earlier age than for the average pavement section. Alternatively, pavements deteriorating at a slower pace than the average sections will hit the trigger values at a later age. This shifting of the curve is reflected in Figure 10.16.

Figure 10.16 Shift in the performance model.



from Deighton Associates Ltd.

Triggering Initial Treatments: After conditions have been predicted for each year in the analysis, dTIMS identifies each occurrence where a pavement section falls into the trigger zone for each feasible type of rehabilitation. This step results in a list of all feasible initial treatments that could be considered within the multi-year program.

Calculating Reset Values: For each treatment that is triggered as a feasible initial treatment, the conditions associated with the section must be reset to reflect the application of the treatment. For example, if one of the feasible treatments is reconstruction of an asphalt pavement, then the PCR should reset to 100, and the PSI and RUT values should return to perfect condition levels. This step is important in considering subsequent rehabilitation activities and for determining the benefit provided by the application of the treatment.

Calculating Subsequent Condition Indices: After resetting the condition levels due to the identification of a feasible treatment, future condition levels must again be forecasted for the remaining years in the analysis period. At InDOT, the future conditions are predicted using the same deterioration models discussed in an earlier section. As the use of the system is further refined, new models may be developed to distinguish the performance of original and overlaid pavement sections.

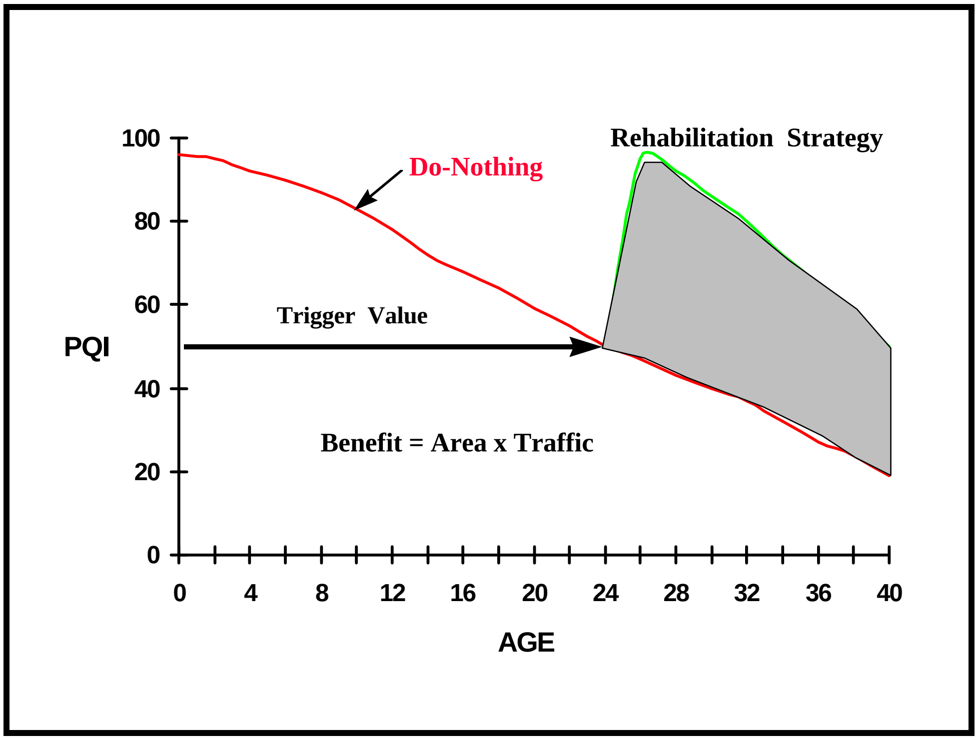
Triggering Subsequent Treatments: In order to determine a more accurate life-cycle cost analysis, all treatments occurring within the analysis period should be considered in the calculation of costs and benefits. At InDOT, a 20-year analysis period is used for life-cycle cost purposes. During that time period, dTIMS considers not only the initial treatments identified in an earlier step, but also one set of subsequent treatments for each pavement section. Subsequent treatments are identified in the same manner as the initial treatments, following the forecasted conditions expected after the application of the initial treatment. No further subsequent treatments are considered in the analysis in order to control the number of possible strategies that are considered part of the analysis.

Calculating Network Level Life-Cycle Costs: The combination of an initial rehabilitation treatment and a subsequent treatment make up a rehabilitation strategy for each pavement section. The life-cycle costs associated with each feasible strategy are then calculated over the entire 20-year analysis period. The estimated network-level life-cycle costs are then used with the benefit provided by the strategy (as discussed in the next section) to determine a benefit/cost ratio for prioritizing projects. Discount rates and inflation rates can be input into the program for consideration in calculating the life-cycle costs. InDOT uses a discount rate of 6% and no inflation in figuring life-cycle costs. As a result of the life-cycle cost analysis, all costs are identified in terms of their present value cost (PVC).

Calculating Benefits: The primary use of the PQI is in the calculation of benefits for each of the rehabilitation strategies for given pavement sections. InDOT uses the area under the PQI deterioration curve as the basis for calculating the benefit provided by a pavement strategy. The area between the do-nothing PQI curve and the curve for the feasible rehabilitation strategies is used as a measure of benefit. This value, multiplied by a factor for daily traffic, results in the benefit associated with each of the possible strategies. It represents the amount of improvement to condition provided by the rehabilitation strategy, the amount of time that strategy provides the improvement, and the number of users expected to benefit from the application of the strategy. The amount of benefit provided by a strategy is calculated to the end of the life-cycle analysis period, or the point at which the deterioration curve hits zero, whichever comes first. The resulting equation for the calculation of benefit provided by a rehabilitation strategy is shown below and in Figure 10.17. The area under the curve is multiplied by traffic to determine the total benefit.

Calculating Incremental Benefit/Cost: Each of the feasible rehabilitation strategies has associated with it a cost (in terms of PVC) and a Present Value Benefit(PVB). In order to identify the most optimal of all strategies, an incremental benefit/cost analysis is performed. The PVC translates all initial and future costs into a single present value cost discounted to the first year of the analysis period. This is done so that all strategies can be compared on an equal basis even though treatments are scheduled at different points during the analysis period.

Figure 10.17 Calculation of benefits for each rehabilitation strategy.



The incremental benefit/cost analysis techniques are well documented in the literature. The first step in the analysis is the calculation of the equivalent uniform annual cost (EUAC) and equivalent uniform annual benefit (EUAB) associated with each rehabilitation strategy.

The following equation is used to calculate the EUAC.

$$\boxed{EUAC = PVC * \frac{(r*(1+r)^n)}{((1+r)^n - 1)}}$$

where: PVC = Present Value Cost

r = Discount Rate

n = Number of Years

The following equation is used to calculate the EUAB for each strategy.

$$\boxed{EUAB = PVB * \frac{(r*(1+r)^n)}{((1+r)^n - 1)}}$$

The EUAB is divided by the EUAC to determine the benefit/cost ratio associated with each treatment (or strategy). The incremental benefit/cost (IBC) of the strategies are calculated using the following equation.

$$\boxed{IBC_j = \frac{(EUAB_j - EUAB_{j-1})}{(EUAC_j - EUAC_{j-1})}}$$

The strategies for each section are then sorted in increasing order of IBC and any negative IBCs (indicating no additional incremental benefit) are eliminated from consideration. The use of IBC is a near optimization approach that selects the best strategy for each road section to maximize benefits without exceeding budget levels.

The use of IBC is used at InDOT to develop the first cut project list that is evaluated by the field committee. As a first cut, no budget level is set so that all projects that hit the rehabilitation trigger levels in the 5-year program period are identified and considered by the committee. The remainder of the program development process is described further in the next section.

Program Development Process: Once the list of prioritized projects has been generated by the computer, field evaluation packets are developed for each of the feasible projects being considered. The packet provides information about the functional characteristics of the pavement, the proposed rehabilitation activity and associated costs suggested by the pavement management program (cost used in PMS analysis reflects project cost and not just pavement rehab costs), the most recent condition information, and other design and construction information. The packet also includes bridge management information to make a complete project recommendation. The field committee reviews each site for approximately one hour, discusses each site as a group, and makes notes about variations in condition or other factors that would influence the scope of the project. After each site has been visited, Preliminary Engineering compiles all of the field notes and develops revised scopes and costs for each project. These revisions are then entered back into the pavement management program and reprioritized. At this point, no other projects are considered in the analysis, and anticipated budget levels for each of the five years can be used to develop the second generation of program lists. The committee reviews the newly prioritized lists and negotiations take place for any changes needing to be made. Although a five-year program is developed through this project, the first three years often features committed projects already in the programming or design stages. The PMS software also allows projects to be committed with no further analysis and combine into the five-year work program. The last two years of the program are set through this process and reviewed annually.

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MODULE 11

OPTIMIZATION

11.1 Instructional Objectives

This module introduces the participants to the use of optimization for the development of multi-year programs. The overall objectives of an optimization analysis are presented and the types of models most commonly used are discussed. Case studies from agencies using optimization are also provided. Upon completion of this module, the participant will be able to accomplish the following:

a) Understand the philosophy of optimization.
b) Identify the concepts involved in an optimization analysis.
c) Identify the types of models used in an optimization analysis.

11.2 Introduction to Optimization

One of the most sophisticated approaches used to identify and select maintenance and rehabilitation treatments involves the use of mathematical modeling techniques as part of an optimization analysis. Unlike ranking and prioritization techniques, which involve a sequential process of identifying and prioritizing projects to fit anticipated budget levels, optimization involves a multi-step process designed to first develop strategies to achieve agency goals and then identify projects that match the strategies.

Optimization has been shown to provide agencies with increased benefits beyond those normally realized by agencies using ad-hoc approaches (*3*). This study has shown that objective approaches to project selection increase agency benefits (in terms of longer service life or greater number of users served) by 20 to 40 percent. Optimization has been estimated to provide an additional 10 to 20 percent benefit beyond heuristic approaches.

Considerations in the Use of Optimization: Optimization is a multi-year planning tool that is more sophisticated and complex than prioritization approaches. An optimization analysis is a multi-step process that involves the following activities.

- Determining the agency goals.
- Establishing network-level strategies that achieve the goals.
- Selecting projects that match the selected strategies.

This type of analysis is capable of analyzing tradeoffs between various projects (as can be done in a prioritization analysis), and can also be used to evaluate any number of strategy choices for each project. In addition, an optimization analysis focuses the recommendations toward the achievement of an overall level of network performance.

Due to the sophistication of an optimization analysis, there are a number of considerations that must be taken into account as an agency decides whether or not to incorporate optimization into its pavement management efforts. These considerations are explained below (*2*). Ranking and prioritization techniques are better understood than optimization is by elected officials and upper level highway agency management, so it is easier to justify program recommendations with these approaches.

- Agencies perceive a loss of control in the planning and programming process due to their failure to understand the optimization process.
- Optimization methods require individuals with strong backgrounds in mathematics, statistics, and operations research, which is beyond most civil engineering curriculums. Individuals trained in the development and operation of these systems are difficult to find and retain.
- Optimization techniques are more dependent on the accuracy of the database so consistency in data collection efforts is more important.
- The mathematical modeling techniques involved in optimization require very sophisticated data processing equipment.

Each agency must make its own decisions with respect to the selection of optimization or prioritization for multi-year planning purposes. The following recommendations should be considered guidelines in determining the right approach for any highway agency (*2*).

- If management wants to exercise significant control over the planning and programming exercises, prioritization is the preferred choice.
- If management wants to take a global view and is willing to put substantial faith in a system, then optimization would be the choice.

Recent surveys of pavement management efforts in the United States and Canada indicate that few agencies use true optimization methods as part of their pavement management efforts. However, those agencies where optimization techniques are being used effectively are pleased with the results of their analysis and have a great deal of confidence in the recommendations provided.

Overview of Analysis Components: The use of optimization methods for multi-year planning requires that an agency establish an overall maintenance and rehabilitation goal that can be defined in mathematical terms called an objective function. In general, objective functions fall into one of two categories:

- Minimization of the overall cost of the program, or
- Maximization of the benefit derived from the expenditure of available funds.

After the objective function has been defined, the agency must then identify any constraints or limitations that must be considered. For example, minimizing the overall cost of the program must be limited so that no individual section in the network falls below a certain acceptable condition level. If this type of limitation did not exist, the lowest overall program cost would be $0, resulting in a decreasing network condition.

Similarly, an objective function aimed at maximizing the benefit must set constraints on the minimum condition and the requirement to use all of the available funding in achieving the maximum benefit (*3*).

Optimization makes use of mathematical programming techniques to identify strategies that allow the selected objective function to be met. Probability is considered in an optimization analysis in a number of ways, including the use of Markov transition probability matrices such as the one shown in Table 11.1. In this example, the pavement network is divided into four condition states. The likelihood of a pavement transitioning from one condition state to another is outlined in the matrix. For example, a pavement in condition state 1 has a 20% chance of remaining in a condition state of 1, a 40% chance of transitioning to a condition state 2, a 30% chance of transitioning to a condition state 3, and a 10% chance of transitioning to a condition state of 4. Although in most cases pavements do not transition from a lower condition state to a higher condition state without the application of a rehabilitation activity, this example includes the effect of routine maintenance practices in moving some pavements in a condition state of 3 up to a condition state of 2 and some in a condition state of 4 to a condition state of 3.

Table 11.1 Markov transition probability matrix.

Current Condition State	**Future Condition State**			
	1	**2**	**3**	**4**
1	0.2	0.4	0.3	0.1
2		0.2	0.6	0.2
3		0.1	0.3	0.6
4			0.1	0.9

In the transition probability matrix, the probability of each event is referred to as the transition probability that represents the likelihood of a pavement section transitioning from one condition state to another. The condition of each pavement section is characterized in terms of *condition states* that represent a specific combination of factors such as distress, roughness, or some other factor. The Markov assumption implies that the next year's condition is independent of how the pavement acquired the current year's condition state (*9*). This limitation can be overcome by including factors such as age and design life of the last rehabilitation action into the definition of the condition state.

In addition to following the transition of pavement sections from one condition state to another, the costs associated with the transitions must be considered. These costs include the initial costs incurred during the construction phase as well as routine maintenance costs incurred each year. Some agencies include user costs and/or salvage costs as part of the total life-cycle cost of a project. A present worth analysis is used to convert the total life-cycle costs into present worth values. The objective of the analysis is to find the preservation policy that best meets the objective of the objective function, whether that means minimizing the total costs subject to meeting certain performance related constraints or maximizing the expected benefit subject to budgetary constraints.

There are a number of decision processes that can be used for an optimization analysis. Heuristic methods, such as incremental benefit-cost, are methods that have been discovered through trial and error to give answers that are close to true optimum solutions. The Markov and semi-Markovian decision processes are perhaps the most common approaches used today. There are other techniques, such as Monte Carlo methods and Fuzzy Set methods, which show promise in future optimization analyses.

11.3 Markovian Decision Process

Because of the large number of possible actions that could be considered for a network analysis, and the uncertainty involved in each event, probabilistic dynamic models are the most often used optimization approach in pavement management. Probabilistic models are important to the analysis so uncertainties in the analysis can be taken into account. Dynamic models are important to address the sequential nature of the decision process. Although there are a number of probabilistic dynamic models that can be used, the one that is best suited for pavement management is the Markov decision process (*2*).

A Markov decision process can be illustrated through the use of a small example (*2*). The example illustrates the use of transition probabilities, costs, and the selection of the optimal long-term policy.

Example of a Markov Decision Process: A small network consists of 100 miles of pavement that may be in one of two condition states: (1) good or (2) poor. At the current time, 80 percent of the network is assumed to be in good condition (1) and 20 percent in poor condition (2). Only two maintenance activities are considered for each pavement section: Do nothing (DoNo), which includes routine maintenance, and Overlay (Over). Transition probabilities have been determined for each combination of condition states and actions. These are summarized in Table 11.2.

Using the information that is known about the pavement network, the probability that a randomly-selected segment in the network would be in condition state 1 in each year can be determined. Similarly, the probability of a segment being in condition state 2 can be determined. These probabilities are reflected in Table 11.3. As shown in the table, the probability of a pavement segment being in a good condition state is 80% for year 1, 64% for year 2, and 67% for year 3.

Table 11.2 Transition probability matrix for the example.

	To Condition States			
From Condition States	**Do Nothing**		**Overlay**	
	1 (Good)	2 (Poor)	1 (Good)	2 (Poor)
1 (Good)	0.6	0.4	0.95	0.05
2 (Poor)	0.01	0.99	0.8	0.2

Table 11.3 Percent of the network in each condition category over time for the sample network.

	Year 1		Year 2		Year 3	
	To Condition States					
From Condition States	1	2	1	2	1	2
1	0.8*0.6= 64	0.8*0.4= 32	0.64*0.6= 38.4	0.64*0.4= 25.6	0.67*0.6= 40.2	0.67*0.4= 26.8
2	0.2*0.8= 16	0.2*0.2= 4	0.36*0.8= 28.8	0.36*0.2= 7.2	0.33*0.8= 26.4	0.33*0.2= 6.6
Total	64%	36%	67.2%	32.8%	66.6%	33.4%

The probability of being in a particular condition state can be reported as the expected proportion of all segments being in that condition state. Using the example shown above, the percentage of pavements in the good condition state started out as 80% of the network and dropped to 64% in year 1, 67% in year 2, and 67% in year 3. For the poor condition state, the percentages started at 20% followed by 36% in year 1, 33% in year 2, and 33% in year 3.

One of the interesting properties of a Markov process is that after several transitions, the system reaches a *steady state* condition in which the probability of being in each condition state remains constant. In this example, the steady state condition is reached in year 3.

In order to conduct the full optimization analysis, the costs associated with each condition state and rehabilitation alternative must be considered. Table 11.4 summarizes the initial and annual costs considered with each alternative. No other costs, such as user costs and salvage values, are being considered in this example.

Table 11.4 Costs for each action.

Condition State	Action	Initial Cost (per mile)	Annual Maintenance Cost (per mile)	Total Cost (per mile)
1	Do Nothing	0	$2000	$2000
2	Overlay	$10,000	$100	$10,100

Using the costs presented above, the annual cost of the policy in each year can be estimated.

This information is summarized in Table 11.5.

Table 11.5 Total costs for the example in each year.

Year	Condition State	Number of Miles	Action	Cost for Given Condition State (in thousands)	Total Costs (in thousands)
1	1	80	Do Nothing	160	362
	2	20	Overlay	202	
2	1	64	Do Nothing	128	491.6
	2	36	Overlay	363.8	
3	1	67	Do Nothing	134	467.3
	2	33	Overlay	333.3	

The results of a number of different repair strategies can be compared following similar procedures. The optimal policy is the policy which establishes the desired long-term performance standards and the minimum budgets required to achieve those standards. The optimal short-term policy may be different. For the short term, the objective is to bring the system to steady state with the desired performance standards within a specified planning horizon, such as 5 to 10 years, at a minimum cost. Due to budget and policy changes that constantly affect actual conditions, steady state conditions are not always reached. Even so, steady state is important for specifying performance goals that guide short-term actions.

The behavior of a highway network under the application of short- and long-term policies is illustrated in Figures 11.1 and 11.2, both of which assumes a 5-year transition period. During the 5-year period, the network condition is gradually increased until steady state conditions are reached. As soon as steady state conditions are reached, both the performance levels and expected budgets will reach a stationary level.

Figure 11.1 Projected performance for the network.

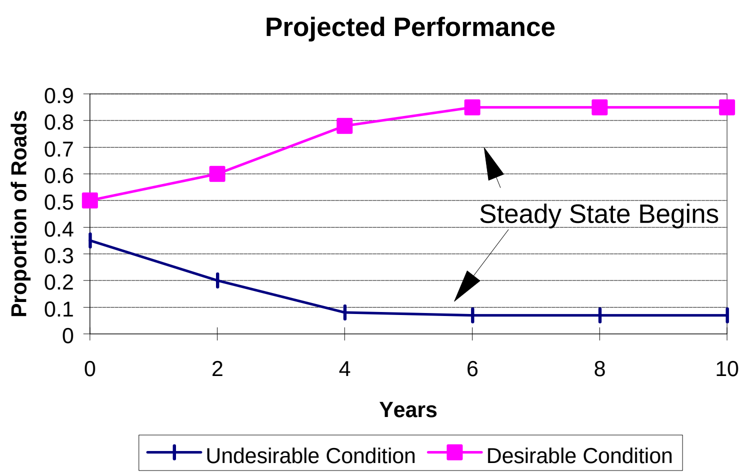
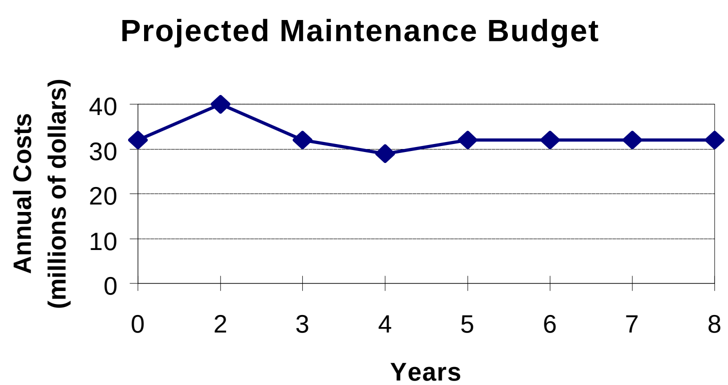


Figure 11.2 Projected maintenance budget.



Advantages and Disadvantages: The literature presents a summary of the advantages and disadvantages associated with the use of a Markov decision process for an optimization analysis as part of a pavement management system (*2*). The following are listed as the advantages to its use.

- Agencies are able to make policy level decisions based on either the minimization of costs subject to specified performance constraints or the maximization of benefits subject to budgetary constraints.

- The probabilities associated with actual pavement conditions are incorporated into the analysis, simulating real conditions. Pavements that may exhibit unusual conditions can be taken into account in the analysis.
- Dynamic decision process models are more reliable than static decision models due to the fact that pavement performance needs to be predicted only for a one-time period in the future. Succeeding time period pavement performance is conditional on the actual performance of the pavement and the actual maintenance action selected. Static decision models require long-term predictions that are independent of how the pavement may perform in the future.
- The Markov decision process provides an integrated analysis of present and future pavement conditions, the choices of present and future actions, and present and future maintenance actions.
- This type of analysis is flexible enough to be customized to the specific needs and maintenance practices of a given agency. For example, different types of pavement distresses can be included, different maintenance alternatives can be considered, and a variety of budgetary and policy constraints can be addressed.

There are also a number of disadvantages associated with the use of a Markov decision process. The main disadvantages are listed below.

- The system requires very sophisticated mathematical modeling techniques such as linear programming. The use of these techniques is not widely understood.
- The computational limits of linear programming methods constrain the size of a Markov decision process that can be analyzed efficiently. In general, the number of condition states in the analysis must be limited to less than 500 states. This translates into a maximum of three distress types for a given pavement type and four severity levels for each distress type. These limits are not excessive from a practical point of view.
- The results of an optimization analysis are more difficult to explain than prioritization approaches. Agency personnel unfamiliar with the techniques of optimization tend to resist the implementation of this type of model. It should be noted that although the development of optimization programs requires expertise in the areas of decision analysis and operations research, the use of these programs does not generally require this same level of expertise.

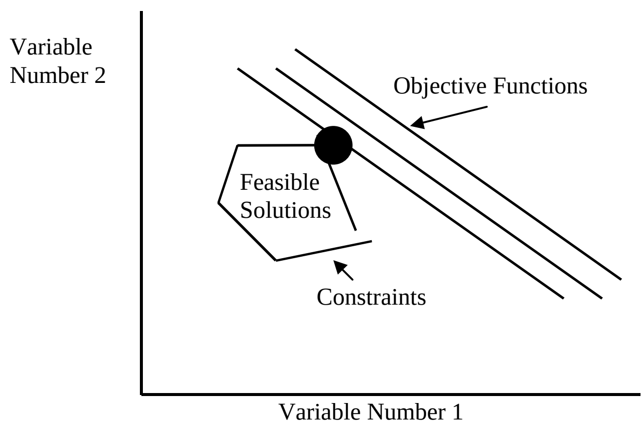
11.4 Mathematical Programming Methods Used in Optimization

In order to identify the optimal strategy for any given network subject to the constraints established, it is important that a sophisticated analysis tool be available. Optimization analyses use mathematical programming methods to solve the objective function of the equation without exceeding the given constraints. There are four predominant mathematical programming methods used in pavement management: linear, non-linear, integer, and dynamic programming (*1*). The objective of any of these programming methods is to find the one solution that is the optimal solution for the given conditions. The constraints of the analysis include the simultaneous equations that cannot be solved uniquely because there are too few of them. The criterion statement that is used to select the *best* solution is the objective function.

The selection of the appropriate mathematical programming method is a function of the type of variables in the analysis (whether they are continuous or not), the form of the objective function, and the whether decisions must be made in sequence. By far, the most common programming method used in pavement management is linear programming (*1*). Dynamic programming is the next most common method followed by non-linear programming. At the present time, no agencies are using integer programming methods for pavement management purposes. These programming methods are explained in more detail in the following sections.

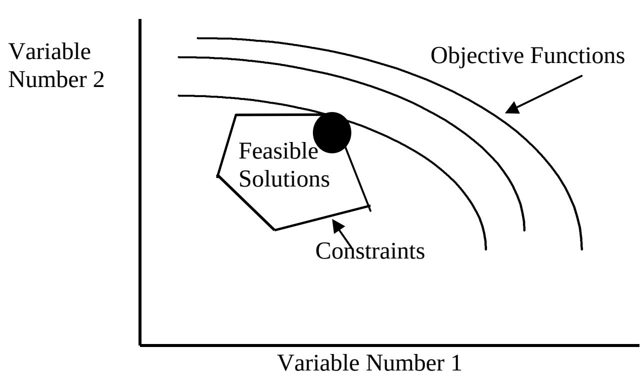
Linear Programming: As illustrated in Figure 11.3, linear programming involves an analysis in which both the objective function and the constraints are linear functions of the variables (*3*). In this type of analysis, the variables are continuous, meaning that they can take on all values that are on the graph. The constraint equation defines the boundaries of the feasible conditions within which all acceptable solutions will fall. The objective function is represented as a straight line which is moved toward the feasible region while keeping its slope. The first vertex it encounters is the optimum solution.

Figure 11.3 Linear programming concepts (*3*).



Non-Linear Programming: Non-linear programming is very similar to linear programming in that it also seeks to find the best solution from an infinite number of solutions using continuous variables. The primary difference between the two is that in non-linear programming, the objective function and some of the constraints may be curvilinear or time dependent. The mathematical manipulations involved in non-linear programming are more detailed, but the principle remains to identify the point at which the objective function first intersects the feasible region. A non-linear programming approach is illustrated in Figure 11.4.

Figure 11.4 Non-linear programming concepts (*3*).



Integer Programming: An integer programming analysis involves variables that are no longer continuous. Instead, the variables can only take on the values of 0 or 1, indicating a decision not to do something or to do it, respectively. An integer programming problem results in a decision matrix that is composed of a series of 0s and 1s, as shown in Table 11.6. The constraints of the analysis force the values of the variables to either be 0 or 1, indicating whether the do nothing or do something option is selected. Other than this difference, integer programming is similar to linear and non-linear programming in the use of an objective function and its constraints. In this type of analysis, the constraints may include limitations on funds, manpower, equipment, materials, and so on (*3*). The objective function seeks to select the projects and alternatives that maximize a benefit or minimize an overall cost.

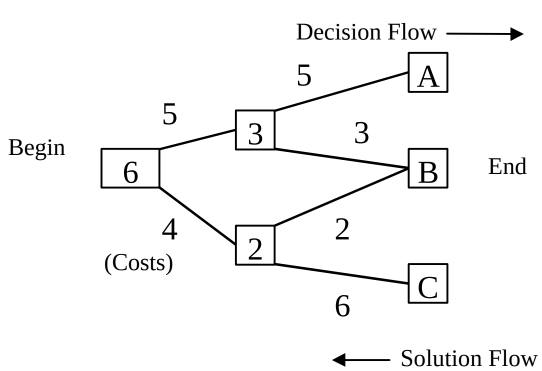
Table 11.6 Decision matrix for an integer programming problem.

Projects	Do Nothing	Seal	Overlay
1	0	1	0
2	1	0	0
3	0	0	1
4	0	1	0

Dynamic Programming: Dynamic programming methods are used when a number of decisions must be made in sequence and an earlier decision dictates what the subsequent decision will be. The sequential decisions in a dynamic programming analysis are normally represented as a network, as shown in Figure 11.5. In this network, each node represents a decision point and the lines represent the costs associated with making each choice. The path with the least cost is identified as the optimal solution.

As can be seen, dynamic programming is used to determine the least cost associated with each decision. The analysis is conducted by starting at the final condition and working towards the beginning point. The path with the smallest sum, or the greatest benefit, is the optimal solution.

Figure 11.5 Concepts of dynamic programming (*3*).



11.5 The Implementation Process

A step-by-step process can be followed to implement a Markov decision process as part of a pavement management analysis. The following steps are outlined in the literature (*2*).

Step 1: Network Division Regardless of the method used for project selection, it is important that the network be divided into road segments. In some cases, fixed segment lengths are used and conditions are assessed periodically over the same lengths. Some systems provide dynamic sectioning capabilities that permit pavement sections to vary depending on the types of data collected or the existing conditions.

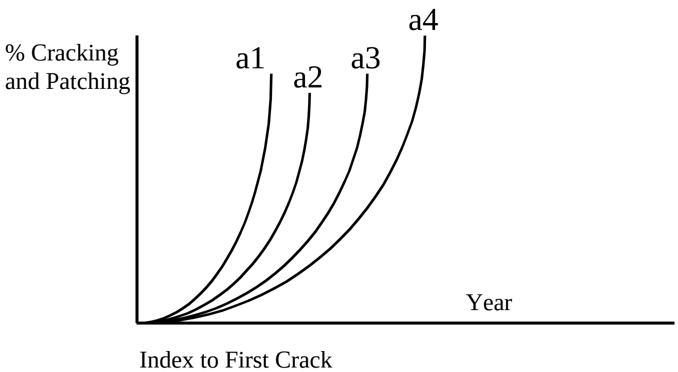
Step 2: Define Road Categories Road categories are established for a pavement network as a means to distinguish pavements that perform differently, have different costs for the same maintenance actions, or which have different relative importance. Factors such as pavement type, functional classification, traffic volumes, and maintenance districts are often used to determine the groups. Regardless of the application of any maintenance or rehabilitation action, each of the segments assigned to a road category remains in its category. In an optimization analysis, each road category is modeled separately.

Step 3: Define Distress States and Condition States for Each Category This step involves the first actions toward the development of the probability transition matrices for an optimization analysis. It involves the development of distress states that identify the combination of specific levels of relevant distress types for pavements in any given road category, and the development of condition states that expand the distress states by adding variables that influence the rate of change in each distress type. For example, distress types that may be included in an analysis include roughness, cracking and patching, and rutting for asphalt pavements. In order to meet the computational restrictions of the analysis, no more than three distress types should be considered and no more than four severity levels should be considered. Many agencies identify the four levels as the threshold levels that would be used to trigger four major rehabilitation actions: do nothing, routine maintenance, minor rehabilitation, and major rehabilitation.

The variables used to define the condition states vary depending on the agency. These can include variables such as the index to the first crack or the change in cracking during the last year. A variable such as the index to first crack captures the differences between the probabilities of deterioration of pavements with no visible cracks but with different most recent non-routing actions. If two road segments have no visible cracks at the present time, the probability of occurrence of significant cracking on each segment during the next year would depend on the index to first crack of the most recent non-routine action. For example, if the index to first crack for a segment was in the range of 0 to 4 years, there would be a significant probability of cracking on that segment during the next year. On the other hand, if the index to first crack was 12 to 16 years, the probability of cracking on the segment during the next year would be negligible. Once cracks do appear, the progression to higher levels of cracking is influenced more by the rate of change in cracking than the index to first crack of the most recent non-routine action. The rate of change in cracking would identify whether the pavement is on a steeper or flatter part of the fatigue cracking curve.

The effect of influence variables is illustrated in Figure 11.6.

Figure 11.6 Effect of influence variables.



STEP 4: IDENTIFY ALTERNATIVE MAINTENANCE ACTIONS This step involves the development of a master list of all feasible maintenance and rehabilitation actions to be considered in the analysis.

STEP 5: ESTIMATE TRANSITION PROBABILITIES This step involves estimating the probabilities associated with the likelihood of a pavement segment transitioning from condition state i to j in unit time. Estimates of the transition probabilities are needed for each road category. The probabilities can be estimated directly from historical data, or they may be estimated based on the experience and expertise of agency personnel.

In addition to the estimates of transition probabilities, the index to first crack also needs to be estimated for each of the alternative actions. This index is used to identify the set of transition probabilities that are appropriate to predict pavement performance following the application of the action selected. Again, this information may be obtained from a statistical analysis of historical data or supplemented with engineering judgment.

STEP 6: ESTIMATE UNIT COSTS In order to identify the costs associated with each action, the initial and annual costs associated with each treatment must be identified. If possible, other life-cycle cost factors, such as user costs, discount values, or salvage values, should be included. This information is then used to calculate the present worth of all future costs. Cost estimates may be obtained from historical records of recent projects. Maintenance costs are typically more difficult to estimate, but engineering judgment may be used.

STEP 7: CALIBRATE THE OPTIMIZATION MODEL This step involves specifying the objective function and constraints for the short- and long-term optimization models. The objective function can be either to minimize costs subject to desired performance standards, or to maximize user benefits subject to meeting budgetary constraints.

First, the long-term model is solved to determine the optimal stationary policy that maintains the road network in a steady state condition. The long-term model provides target performance goals for the network.

The short-term model is solved next with the objective of bringing the network from its present condition to the target performance goals determined by the long-term model. The short-term maintenance are allowed to be non-stationary so that a different maintenance action may be taken for the same condition state at different time periods. Short-term performance standards are also specified to permit a gradual transition from the present to the desired network conditions. The short-term model then finds the maintenance policies that would minimize the total expected cost (or maximize the total expected user benefits) during a specified transition period subject to meeting both the short-term performance standards as well as the long-term target performance goals.

Two options are used to specify performance standards for the optimization models. The first option consists of identifying desirable and undesirable condition states, and then specifying the minimum proportion of the segments that should be maintained in the desirable condition states and the maximum proportion of segments that are permitted to be in the undesirable condition states. In the second option, the user benefit of maintaining a segment in a given condition state is expressed on a relative value scale of 0 to 1. A desired performance standard is then expressed in terms of the minimum expected user benefit that should be achieved by a maintenance policy.

Step 8: Develop Computer Software A modular software system is necessary for the optimization analysis. The system should contain a cost module, transition probability module, optimization input module, optimization module, and report writing module to be most effective. The optimization input module is used to generate a matrix that can be solved using mathematical programming methods contained in the optimization module. The most appropriate programming method must be selected based on the form of the objective function and the type of variables (whether they are continuos or not). Linear programming is the most common approach used in pavement management (*1*).

Step 9: Prepare System Documents and Training Program Technical documents that outline the system implementation should be prepared to provide the agency with information regarding the modeling approach, its constraints and objective functions, and other important characteristics. Training materials should also be provided to assist the agency in learning the capabilities of the system and for future training efforts.

Step 10: Update and Maintain Models and Software The recommendations from an optimization analysis are only as good as the models from which they were made. The reliability of the performance models, cost models, and treatment models should be evaluated at least annually to continue to reflect existing conditions and agency policies. As new technology becomes available, analysis modules should be updated to reflect these new capabilities.

11.6 Case Studies

The Kansas, Alaska, and Arizona Departments of Transportation have used similar pavement management systems that feature network optimization models. The systems have all been developed by the same consultant and enhancements have been added over the years since the original implementations. The Kansas pavement management system (PMS) has been documented in the literature (*1*). It is reprinted here as an example of an optimization analysis.

SYSTEM OVERVIEW: The Kansas Department of Transportation (KDOT) PMS consists of three components: a network optimization system (NOS), a project optimization system (POS), and a pavement management information system (PMIS). The PMIS provides the information necessary to run the NOS and POS analyses. The NOS has been operational since 1986; the POS was not fully operational at the time the case study was written in 1995.

KDOT collects condition information for its highway network on an annual basis. The agency evaluates three distress types for each of the surface types used on the network, and rates extent and severity. KDOT monitors rutting on all pavement types, but this information is used primarily in safety evaluations; the agency also collects roughness data. The result of the annual survey is a summary of pavements in 1 of 27 distress states, which are used to simplify the assignment of feasible rehabilitation actions and costs and to predict performance.

Pavement actions are considered at several levels within this system. The major modification program is intended to improve the safety and service of the existing highway system. Work in this category includes reconstruction or rehabilitating pavements, but focuses primarily on widening traffic lanes, adding or widening shoulders, and eliminating sharp curves and steep hills.

Another level, called the substantial maintenance program, is used to protect the traveling public and its public investment in the highway system by conserving the condition of the network as long as possible. Resurfacing projects are included in this category.

The substantial maintenance program is developed through optimization goals established in the NOS. At this level, pavement rehabilitation and maintenance policies that would minimize the agency’s total costs, subject to meeting desired performance standards or maximizing performance standards for a fixed budget, are set. The NOS outputs list the percentage of all miles in a given road category recommended for each of three categories of rehabilitation actions - routine maintenance, light rehabilitation, and heavy rehabilitation. The optimal policy for a given year is also provided in terms of condition states, the optimal action for each state, the proportion of the total mileage in each condition state, and the unit cost for each recommended action.

Project locations selected by the NOS are then investigated further as part of the POS analysis, and detailed site-specific data are collected for the candidate projects. At this level, deflection measurements, detailed distress data, and cores are used to identify the optimal rehabilitation action or initial design for each project. The POS analysis is specifically designed to address the engineering and technical decisions required in pavement rehabilitation using site-specific actions, cost, and engineering data.

SYSTEM COMPONENTS: The databases, condition evaluation, network optimization system (NOS), and project optimization system (POS) form the basis for the PMS.

Databases: KDOT uses two components in its pavement management analysis. The first, called CANSYS, is the database on the mainframe computer that supports the major modification program for safety improvements. The PMIS is the database on a minicomputer that contains the necessary information for the NOS and POS models to run. The PMIS database is a relational database to assist KDOT in responding to both standard and ad hoc queries. Information is uploaded and downloaded between the two databases.

Condition Evaluation: Mile-long highway segments are monitored yearly at the network level. Because of the computational requirements of the NOS linear programming algorithm, only three distress types are considered for each of the pavement types included in the network. The distresses selected for these surface types are presented in Table 11.7. Rutting is also measured on all flexible pavements. A current enhancement effort is underway to change the flexible pavement distress types to roughness, transverse cracks, and rutting.

Table 11.7 Distress types considered for each pavement type.

Pavement Type	Distress Types
Portland Cement Concrete Pavement	Roughness Joint Distress Faulting
Composite	Roughness Transverse Cracking Block Cracking
Full-Depth Bituminous	Roughness Transverse Cracking Block Cracking
Partial-Depth Bituminous	Roughness Transverse Cracking Fatigue Cracking

The Markov optimization models in the NOS use condition states to evaluate the performance of various pavement sections and the costs associated with their repair. A total of 216 possible condition states are defined for the program to reflect the specific combinations of distress levels and levels of variables that influence the rate of pavement deterioration. The two primary influence variables are the indices to the appearance of the first distress and the rate of change in the distress. The results of the condition survey are used to determine the current condition state of each individual mile segment in the network.

Condition states are further divided into distress states, which are established for the three levels of each distress type. The system uses 27 distress states to simplify the assignment of feasible rehabilitation actions, costs, and the pavement performance models used in the analysis.

Projects that are evaluated at the project level (in the POS) receive more detailed investigations to assist in identifying the optimal rehabilitation action for an individual highway segment. Data collection includes deflection measurements from a Dynaflect, detailed distress data, and laboratory tests on cores and soil samples.

Network Optimization System (NOS): The NOS uses linear programming to develop optimal policies to maintain an acceptable performance level for the state's highways at a minimum cost. Transitions between distress states are used to assess the current level of needs within the state, as well as to forecast future needs for a multi-year optimization. At the network level, pavement maintenance and rehabilitation policies are established to minimize the total costs to meet desired performance standards, or to maximize performance for a fixed funding level. Standards are developed for 23 road categories, which are established based on functional classification, pavement type, roadway width, and traffic loading. In 1994, the NOS was moved off the mainframe computer and installed on a Pentium: OS/2 platform.

The primary outputs of the NOS include the following: annual "minimum" rehabilitation budgets over a selected planning horizon, such as 5 years; locations of candidate rehabilitation projects; maximum performance achievable from a fixed budget; and optimal rehabilitation policies (*3*).

Project Optimization System (POS): Once a candidate portfolio of projects has been identified from NOS analysis, a detailed investigation of its condition is performed as described above. The data are evaluated in the POS, with the intent of identifying the set of initial designs for each project in the portfolio, which maximizes user benefits. Alternative rehabilitation actions are evaluated using site-specific information and mechanistic response variables in the POS performance prediction models. The budget for the portfolio and the performance for each of the individual project segments are constrained by the optimal policies identified by the NOS. At the present time, user benefits are evaluated in terms of a subjective rating that is related to pavement condition levels. This results in an optimization strategy that maximizes system mileage in a high-performance level over time, or minimizes the maintenance levels required by the state's forces. In 1994, the POS was also moved off the mainframe computer and installed on a Pentium: OS/2 platform.

System Applications: The development of the KDOT PMS began with a 1979 *Issue* paper (*3*). Recommendations from that paper called for a system that contained formal performance prediction and optimization capabilities. A consultant was hired to assist in developing the system for the state using a Markov decision process to model the highway network.

A PMS steering committee was appointed to provide the overall direction for the PMS implementation within the agency. This committee represented the top management within the organization. A pavement management task force was also organized to supervise and assist the consultant in PMS development. Representatives from the bureaus of materials and research, construction and maintenance, planning development, and districts were participants in the task force.

At the present time, the PMS is located in the Division of Operations (materials and research). This division uses funding levels for rehabilitation, developed by the

Division of Planning and Development, to establish a pavement rehabilitation program based on the PMS recommendations.

KDOT has realized significant benefits as a result of its PMS implementation. These include decision support from KDOT executive management and funding support from the Kansas Legislature. The agency also reports that the resource allocation for preservation projects is optimized.

System Constraints: KDOT has experienced several hindrances during its PMS implementation primarily due to the complexity of its system, which requires sophisticated computer equipment and system analysts who understand the Markov process. At times, the system can be difficult to understand for those not familiar with its complexities; however, KDOT has had a successful experience overall with the system.

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MODULE 12

PMS FEEDBACK PROCESS

12.1 Module Objective

This module will emphasize the importance of a PMS feedback process. This module will stress the need for an active feedback process to be included as part of the planned PMS implementation effort. The feedback loop also provides an effective process for the agency to evaluate the effectiveness of its pavement design and construction practices through an ongoing analysis of its pavement performance models. The PMS developed in Washington State is presented as a case study in this module.

Upon completion of this module, the participants will be able to:

- Explain why a feedback loop is important to the operation of a PMS.
- Describe the various processes in a PMS that need to have a feedback loop established, and the types of feedback that is required.
- Describe how to establish a feedback loop.
- Describe the possible benefits of a feedback loop to other agency needs.

12.2 Introduction

The 1990 AASHTO Guidelines for Pavement Management Systems (*4*) describes the Feedback Process as one of the primary components of a generic pavement management system. To quote from the guide:

> *"Pavement management systems, similar to any other engineering tool must be reliable in order to be credible. The feedback process is crucial to verify and improve the reliability of a PMS.*
>
> *A measure of the PMS reliability can be achieved by comparing:*
>
> - *Actual costs of maintenance, rehabilitation, and reconstruction (available through contract bids and agency records) with those used in the PMS analysis*
> - *Field observation of pavement conditions and traffic with those predicted by PMS models.*
> - *Actual performance standards achieved with those specified in the PMS analysis.*
> - *Actual projects rehabilitated or reconstructed and the treatment applied with those recommended by the PMS.*
>
> *If significant discrepancies are found between actual data and PMS projections, relevant PMS models and parameters should be revised appropriately.*
>
> *At the start-up of a PMS, historical performance data may not be available to calibrate PMS models. Such calibration may need to be performed using engineering judgment and experience. With time, PMS models can be systematically calibrated using data from pavement condition surveys and construction records, thus improving the reliability of and confidence in PMS recommendations.*

It should also be noted that feedback information can also be useful: (1) for agency research programs, (2) to evaluate the influences of construction on performances, and (3) as a measure of the effectiveness of methods used for design of new and rehabilitated pavements."

Under the chapter on development and implementation the Guide adds these additional recommendations.

"The pavement management system should be reviewed periodically to make certain that it is achieving the original objectives. Follow up provides the opportunity to identify and make improvements in the system. Feedback is essential to the long-term success of a PMS and to maximize its ultimate benefit to the agency.

A pavement management system must be flexible enough to allow for improvements or modifications over time. It should be considered as a dynamic system, not static. However, frequent (major) changes should not be made more often than once every five years, but minor changes can be made as required. Minor changes or enhancements that simplify or streamline the process or improve economic analysis with no adverse effects on results should be made as needed. Changes which would significantly affect the database requirements, prediction models, economic analysis and type of report required would be considered major modifications and should not be made more frequently than five-year intervals in order to completely evaluate PMS performance and identify all of the improvements needed for a useful PMS. Changes in PMS should only be made when considered necessary by the PMS staff and agreed to by the Steering Committee."

Pavement Management Systems start as a basic concept that fits the description of the generic systems described in the guide but in use they must evolve into well documented, intuitive, and consistent information providers that help engineers make better and more supportable decisions in the development of their construction program. As indicated in the recommendations from the AASHTO Guidelines PMS are not static but dynamic systems that must evolve and improve with time to be of the most use. When a PMS is developed and implemented, a system and data review and improvement plan should also be established as part of the implementation plan. Particularly after the PMS is first implemented, model development is primarily based on limited data or simply expert opinion. These models will usually be within some reasonable range of what actually happens to the pavements to get the system started but they almost always can be improved upon as data is collected over time. As an example let's assume that one of the models in the PMS shows that a 2 inch overlay with preleveling lasts 15 years but the network data shows that the timing is closer to 11 years. Will that have an impact on the results of the PMS network analysis program? The answer is a resounding yes! This can make a *36%* difference in annualized costs in an analysis system that differentiates between treatments with only a couple of percent difference in annualize cost.

For the information provided by the PMS to be fully utilized it has to be very defensible, thus supportable with real field data and consistent with actual experience in the field. Thus in reality developing, maintaining, and utilizing the feedback processes to make the information provided by the PMS as true an image of the pavement network it represents is as important to the long term utilization of a PMS as the initial development and implementation of that system.

12.3 Feedback Plan

Almost all items considered in a PMS should be reviewed periodically and included in the feedback processes. The PMS should not be static because few of its individual parts are static.

The data that is collected and used in a PMS should always be processed with some type of quality control to ensure that the quality of the data is defensible and consistent with its use. However there should also be periodic checks as to what is collected and how is it used. For initial PMS development the AASHTO Guide and others strongly recommend that a PMS be developed under the guidance and support of an in-house PMS steering committee. This recommendation is largely based on the need for the PMS to be accepted and indeed supported across interdepartmental groups. However, one of the usual aspects of a system developed under the guidance of a committee is that a lot of items are usually included in the system to meet the separate needs or desires of the individuals on the committee. In time, the actual working system will be used primarily by those who truly need and use the information most. Over time and use, it will become somewhat self evident what information and analysis processes are actually used and what information or processes are not used. The PMS obviously should be well planned but it takes actual practice and experience running the program and testing the quality accuracy and reasonableness of the information that comes out of the program to finally work out all the details. At the latter stages of the implementation, a good follow-up plan should be developed. The follow-up plan shoud re-confirm the operational process envisioned in the development of the PMS. It must check the data collection and processing procedures to confirm that they satisfy their intended purpose and identify any data collection or processing procedures that are not used or were not as defensible as was envisioned during the initial development. The following sections discuss the basic areas of a PMS that should be considered in establishing follow up procedures.

Pavement Peformance Models (Individual or Family Curves): During the development of a PMS the service life or performance of each pavement type and rehabilitation treatment is estimated from limited agency data or from the collective opinion of pavement experts within the agency. These performance models must be recalibrated with actual field data and operating processes to ensure confidence in the system.

Usually a minimum of three collection cycles or data points are required to develop the most basic performance curve for individual projects. For the development of a pavement performance model for a family of curves for similar projects in a network, three observation cycles will provide more information since the three cycles will cover a wider time span for a group of projects. However, with the natural variation in the accuracy of the condition data that is collected, three cycles will provide only a very rough first estimate. Performance curves developed with this limited amount of data may not prove to be as good a prediction of the final pavement performance as expert opinion. Five observation cycles provide a much better estimate of performance because this number of cycles allows more natural variation in the data collection. Obviously 8 and 10 collection cycles are better yet. If an agency conducts pavement surveys at two year cycles then five to eight cycles will usually encompass the full performance cycle of an average pavement and thus provide a good base of data to develop individual pavement performance curves and family pavement performance models.

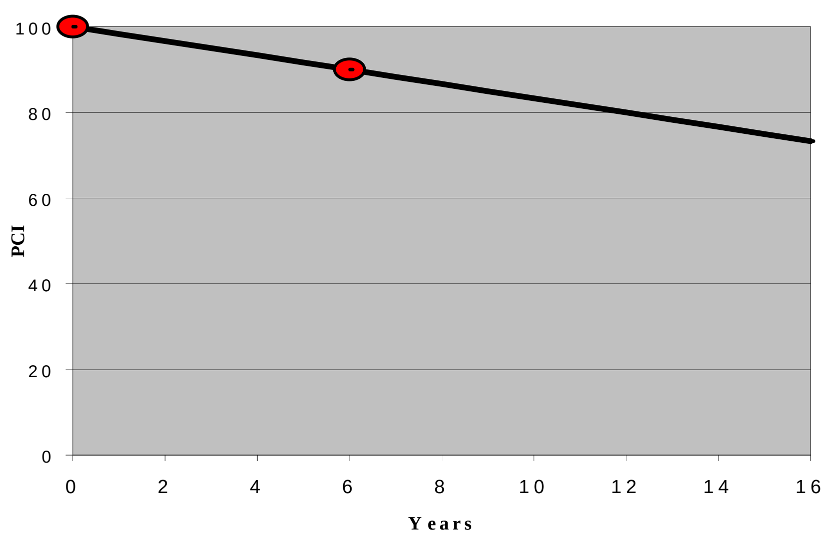
In the development of the Washington PMS, the original development of the condition indices and the pavement performance models began with three sets of data and was implemented when there were five sets of condition data available. From the initial development through the implementation of the PMS, there was a clear improvement in the project level pavement performance curves developed by the system. This was probably due more to the additonal data available over that time frame than improvements in the system, as the basic pavement performance models did not change through the development and implementation of the system (*1*).

To help provide an explanation for the increased accuracy that additional data points provide, consider the following example. A typical pavement performance trend for a flexible pavement section is depicted by a series of pavement condition index points which represent the measured pavement condition over time. It was assumed that the condition surveys were begun six years after the pavement was constructed and continued on two-year cycles. Figures 12.1 through 12.5 show the resulting predicted pavement condition trend (based on regression analysis) as each observation of the pavement condition is added to the data base.

A single observation cycle which usually produces two points (since a new or resurfaced pavement is assumed to start at a PCI of 100) can only provide a straight line prediction as shown in Figure 12.1. This early straight line prediction which represents the earliest and slowest deterioration of the pavement usually predicts an unrealistic long pavement service life.

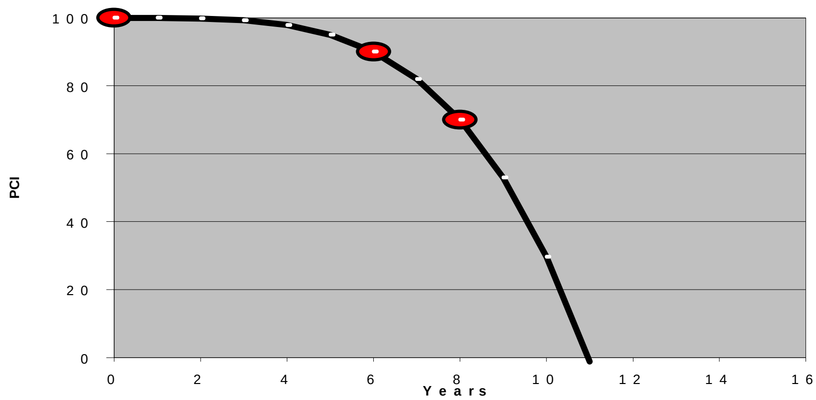
Figure 12.1 A typical pavement performance curve after 2 condition surveys.

With two observations, or three points as shown in Figure 12.2 an exponential equation



can be developed that fits all three points perfectly. The prediction provided by the curve that fits through all three points is easy to compute mathematically, but it may still not provide a prediction that is better than that provided by expert opinion. It is usually, however, a large improvement over the two-point prediction.

Figure 12.2 **A typical pavement performance curve after 3 condition surveys.**



The addition of the data from the third condition survey provides four points on the graph. Four points are usually the minimum number of points necessary to conduct a reasonable regression analysis and produce an actual error of estimate and a measure of best-fit (R^2). The total of four points and subsequent regression curve which best fits those points provides a reasonable prediction of the final performance life of the pavement section as can seen in Figure 12.3.

After the addition of data from the fourth pavement condition survey, which produced the fifth point on the graph in Figure 12.4, the pavement performance prediction from regression analysis is now very close to the final performance curve. At this stage, the data will usually provide a pavement performance model than that first established by expert opinion.

The addition of the data from the fifth pavement condition survey, produces the final pavement condition curve shown in Figure 12.5 which represents the full life cycle of the pavement section.

Figure 12.3 A typical pavement performance curve after 4 condition surveys.

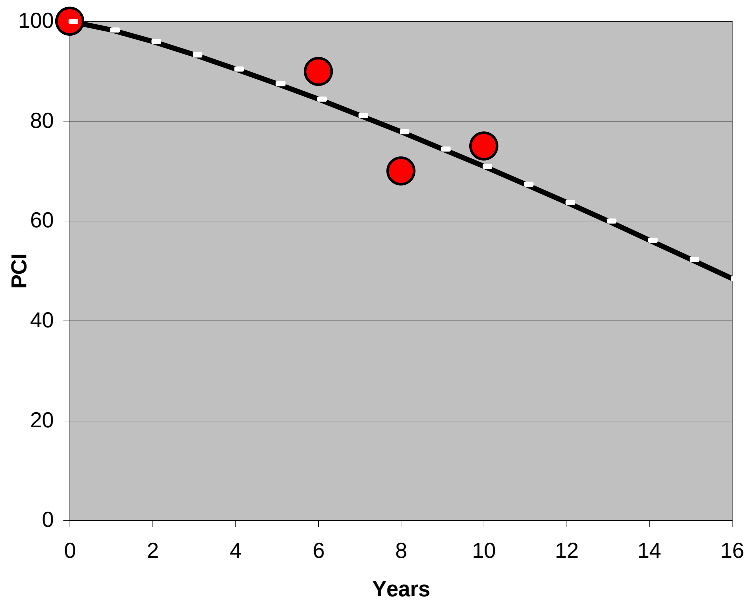


Figure 12.4 A typical pavement performance curve after 5 condition surveys.

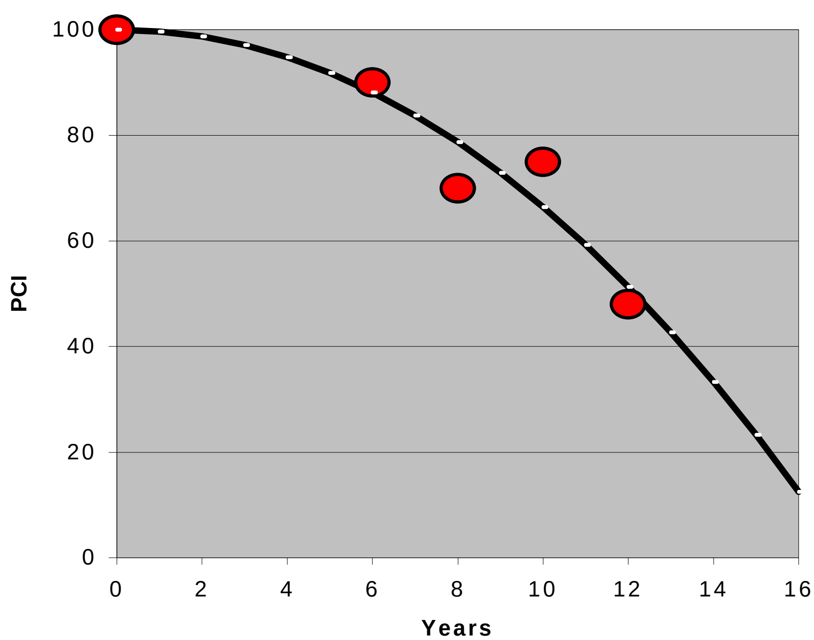
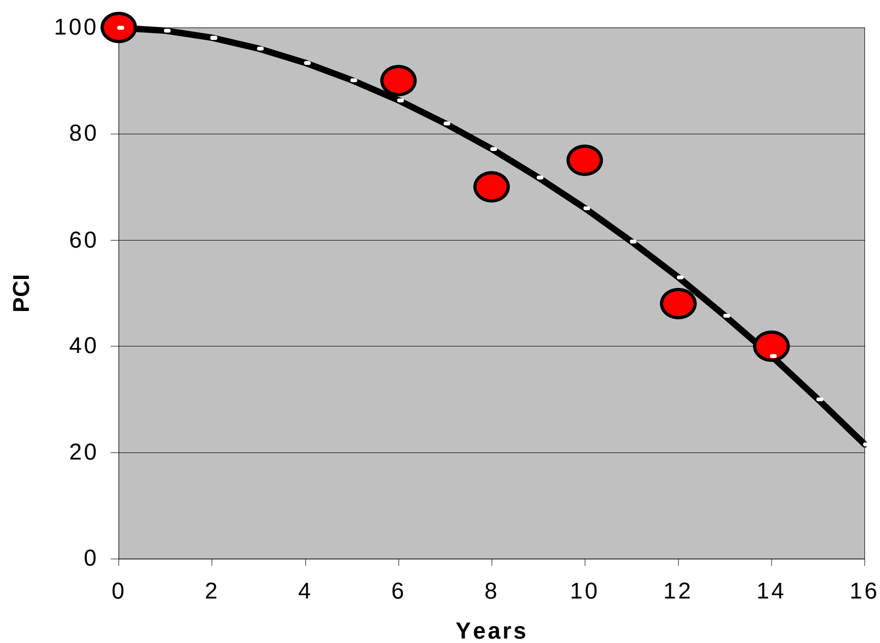


Figure 12.5 A typical pavement performance curve after 6 condition surveys.



The typical performance curves used in this example are representative of fairly good (accurate) pavement conditions surveys. In real world practice, the actual PCI values could be more variable and the resulting predicted pavement condition trends much more variable.

Example of Pavement Performance Feedback Loop: In 1986, Washington State DOT conducted a small in-house study to see how well the pavement performance analysis progran predicted future pavement conditions. The pavement performance analysis program computed unique pavement performance curves for each project length segment for the entire highway network. The project specific pavement performance curves were determined by conducting regression analysis that produced pavement performance curves that best fit the biannial pavement condition index values for each individual project. The study compared the pavement condition indices from the 1984 PMS program predicted for 1986 to the actual indices measured for all projects in 1986. The finding of this small study indicated that the pavement performance models were in general, over predicting the service life of the projects (*2*).

As a result of this study, WSDOT modified its procedures to predict the pavement condition for each individual project in the PMS. The improved procedure consisted of attaching a curve that represented the average performance for that treatment (from a family of curves), to the last measured condition index value. The curve which represented the expected average performance was used to establish additional points that represented the most likely future condition. A final pavement performance curve was developed by using the existing regression analysis procedure but including both the measured points and those representing the average curve. This proved to be a much better predictor of the future pavement condition than simply regressing through the existing measured points. This improved pavement performance analysis procedure was checked again in 1988 and was found to provide a significant improvement over the earlier simple regression procedure. To keep the process as accurate as possible, the average pavement performance curves for each pavement type and treatment have now been re-developed every two years. Like the earlier work, the average pavement performance curves were developed for each pavement type and treatment for the different geographical and environmental regions within the state. This information indicated that there was usually two to three years difference in the average service life of a typical 2 inch overlay in different environmental regions of the state.

TREATMENT TYPES AND TRIGGER LEVELS:: During the development of a PMS, basic rehabilitation treatments are established that will be used in the PMS network optimizing program. These treatments are established based on limited agency data or from the collective opinion of pavement experts within the agency. In many cases the development of a PMS causes the agency to establish, for the first time, a basic policy on what rehabilitation treatments are used by the agency and under what condition (trigger) each specific treatment is used. The selection of treatments and the conditions and condition levels that trigger each specific treatment selection is usually determined by general agreement of those developing the PMS or developed by consensus of a PMS Oversite or Steering Committee. They are seldom developed through a detailed study using actual PMS condition data and PMS analysis programs.

Thus, the treatments first established during the development of the PMS must be reviewed with real PMS network data and actual case studies using the output from several PMS network optimization runs. This follow-up review should test the actual output from the treatment selection process for reasonableness. A special effort needs to be made that most engineers that use the information from the system agree with how reasonable the treatments are, and under what condition each should be used.

In addition to the treatments that have been developed for use in the PMS, the trigger levels at which each treatment is considered also needs to be checked. In many cases the trigger levels that were first developed for the PMS are a rough estimate at best. These are often developed in anticipation of how they will trigger treatments in the PMS, but there is no substitution for actually running the PMS with real data. This is the only time the actual impact of the trigger levels on the output of the network level analysis can be observed. The trigger levels should be checked after the first PMS run to confirm that there are no unique problems caused by the treatment levels included in the system. After two to three years, a special effort should be made to review the trigger levels and their respective impact on the output from the network optimizing analysis. Trial and iterative network optimizing analysis should be run to confirm the relative levels of the trigger values and to determine the relative sensitivity of the various trigger levels. As a general recommendation the treatment types and trigger levels should be checked at least by the third year after initial implementation of the PMS. As it may take another 1/2 to 1 year to complete this rather detailed work, especially if adjustments and several iterations are required, a three-year period is not too soon to begin a review.

The follow-up study is clearly needed to demonstrate how the selection process is working and to get confirmation from the PMS Oversight Committee that the agency fully supports the results of the analysis program and the resulting projects and treatment selection. However, this follow-up check and confirmation process is also extremly important to help establish that the PMS is providing information the engineers in the agency actually will use in the development of the construction program.

Example of Treatment Feedback Loop: The Washington PMS was developed using the pavement condition data that had been collected to support a priority array form of pavement management process that was implemented in the late 1960’s. Since 1969, pavement condition data was collected every two years. The earlier pavement performance models from the priority array system underwent several refinements before the PMS was implemented. Thus by the time the PMS was implemented, performance models had been developed for a wide range of treatments. One treatment that consisted of a “maintenance hot seal” (3/4 inch to 1 inch of 1/2 minus hot mix) was found to have a questionable service life. Where most other treatments showed reasonable performance lives with a normal service life distribution, the thin hot seals had a service life distribution with two peaks: one peak occurred around 2 to 3 years after construction and another peak occurred around 7 to 8 years. Further investigation indicated that the short service life projects all had deteriorated quickly because they had been placed on structurally inadequate pavements while the longer service life treatments had been placed on pavements in fairly good condition (structurally sound pavement).

From this information, the agency ceased to place thin maintenance hot seals on structurally inadequate pavement, and limited their use to structurally sound pavement. After 4 to 5 years, results indicated that the thin hot maintenance seals were now providing the expected 6 to 9 years service life with a fairly normal distribution.

Treatment Costs: Treatment costs may be reviewed at somewhat longer time intervals than the performance models, treatments, and triggers covered earlier. Since treatment costs are compared together, the relative cost differential between treatments are more important to the network analysis than total costs. Thus, if there is no major change in relative costs between treatments from year to year then treatment costs may be inflated each year for five or more years without having much effect on the network analysis results. To confirm that there has not been a significant relative change between treatments they should be reviewed periodically. Obviously, if there are changes in treatments, then the relative treatment costs should be reviewed at the same time. A detailed recompilation of all treatment costs should be considered at five to six years.

User Costs Models: User costs models follow the same relative pattern as treatment costs. The relative difference in costs between user and treatment costs has a greater importance in the network analysis than the effect of the total costs. This is particularly true for comparing and selecting projects, their treatment and timing. The total network costs are most important when an agency is analyzing total construction program funding needs. Since most agencies do not make annual requests for increased budgets, most of their cost models are analyzed, and possibly re-computed, as part of this process at time intervals of 4 to 8 years.

DATA QUALITY, USE, COST: Good quality control of inventory and condition data is essential to the success of a pavement management system. The data must be accurate, repeatable, and consistent from location to location and from year to year, and representative of what actually exists in the field. Training of personnel and/or calibration is necessary to assure long term confidence in the system and its results or output (*4*). This is one of the continuing processes that clearly should be in place in a functional PMS, but certain aspects also fall in the follow-up category.

The quality control effort should be a part of the ongoing data collection and storage procedures. There should be periodic checks made particularly after implementing a PMS to determine that the quality standards established for the data satisfies the needs of the PMS. If the quality standards are set too low, then the quality of the information provided by the PMS will likely suffer as will its usefulness. If the quality standards are set too high, then the operational costs of the PMS are higher than necessary. A sensitivity analysis is a very useful tool to confirm the quality standards set for the PMS input data.

One final question should also be asked about the input data used in the PMS process, and that is whether the data will be used at all. If the data is not used then the cost of collecting and storing that data competes with data that is or could be used in the system. Agencies simply can not afford to collect and store data that someone has determined that it *would be nice to have*. There must be a demonstrated use for the data or it should not be collected. Three to four years after a PMS has been fully implemented the quality and utility of all data collected and stored for use in the PMS should be reviewed and re-justified.

Other Areas of Feedback: In the 1990 AASHTO Guidelines for Pavement Management Systems it was noted that “feedback information can also be useful: (1) for agency research programs, (2) to evaluate the influence of construction on performance, and (3) as a measure of the effectiveness for methods used for designing of new and rehabilitated pavements (*4*).

The following are a few examples where PMS information has been used through a specific feedback process to provide information in areas outside of the PMS operations.

Pavement Construction: In 1987, Linden (*6*) conducted a special study to look at the effects of air voids on the performance of hot mixed asphalt concrete pavement. It was found that there was very limited field data that could be used to determine the effect of air voids on the performance of asphalt concrete pavement. Thus, his study consisted of conducting a literature review and a survey of state highway agencies through the use a questionnaire, which was sent to 48 of the 50 states.

At the same time, Washington was participating in a small FHWA study to develop pavement performance relationships based on accumulated years and accumulated ESALs (*5*). An attempt was made in this study to combine limited construction based air void data in a small set of 70 projects (less than 5% of the network), from the PMS data base. In this study, the average pavement service life was estimated for five groups of the individual projects based on the average air void content from contract records. The relative loss in service life was then determined for each group of projects, which produced the following relationship (*6*).

Table 12.1 Loss in service life as a function of increased air voids (*6*).

Air Void Content	Loss in Service Life
7	**0**
8	**2**
9	**6**
10	**17**
12	**36**

The results of the Linden and WSDOT study were then compared (*6*) with the following loss of service life reported from both sources.

Table 12.2 Effect Of Compaction on Pavement Performance.

	Pavement Life Reduction (%)		
Air Voids	**Literature**	**Survey**	**WSDOT**
7	0	7	0
8	10	13	2
9	20	21	6
10	30	27	17
11	40	38	
12	50	46	36

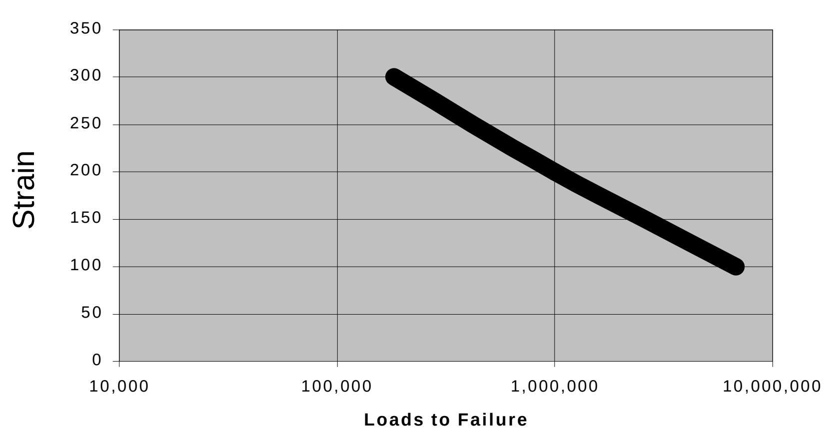
Though the three sources of information do not fit perfectly, they still fit reasonably well together (*5,6*).

Pavement Design: In the mid to late 1980's a research program to develop a mechanistic–empirical pavement design procedure was initiated in Washington (*7*). In this project, a mechanistic based overlay design procedure was developed as well a back-calculation procedure to estimate pavement layer stiffness from in-situ deflection testing and a elastic multi-layer analysis program.

The mechanistic-based overlay design procedure estimates the cumulative damage caused by the predicted truckloads over the design life of the existing pavement and overlay. The mechanistic part of the program determines the stresses and strains caused by the truckloads at various pavement layers throughout each year. The empirical part of the program estimates the cumulative fatigue damaged caused by the range in strains experienced throughout the year in the pavement section being analyzed. The damage relationship developed between strain and fatigue damage was developed based on the observation of pavement deterioration at 21 pavement test sites established at the beginning of the study. These sites were established based largely on information from the PMS, consisting of construction history, traffic levels, pavement performance curves, and environmental regions. This was followed by a much more detailed site evaluation and materials testing program as well as an in depth traffic analysis. The pavement deterioration information from the project specific PMS as well as more detailed site specific crack mapping was used to calibrate the strain versus pavement fatigue cracking model used in the design procedure.

The damage relationship used in the WSDOT pavement design procedure can be shown as follows on a graph of strain versus the number of load cycles to cause 10% fatigue cracking in the pavement.

Figure 12.6 **Fatigue damage model for mechanistic-empirical design procedure (*7,8*).**



Although 21 sites were monitored during the study only a small group of the projects had deteriorated enough for use in establishing the pavement damage models used in the design procedure. In 1995, the DOT revisited the pavement damage relationships used in their mechanistic – empirical overlay design procedure.

An in-house study was conducted which looked at the fatigue damage experienced at a somewhat larger set of locations. In the study, 31 sites were selected from the PMS data base as well as recent project design files. The sites were selected based on having good traffic data from fairly close Weigh-in-Motion (WIM) sites as well as deflection tests and core data giving pavement layer thicknesses. The deflection data and layer thicknesses were used to estimate stress and strains in the pavement layers. The WIM data and basic traffic files in the PMS were used to estimate the cumulative truck loading for each site. The individual distress data from the PMS and the pavement performance curves were used to determine the amount of fatigue damage each site had experienced each year since the last overlay was constructed.

The study found the same general range in damage versus strain found in the first study. However, the average damage was found to be a little greater at the various strain levels (*8*). The actual design procedure allows the user to input the relative amount of damage versus strain used in the design analysis. This study indicated that a little more severe damage factor should be used in the overlay design analysis program, which will result in slightly thicker overlays.

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MODULE 13

INSTITUTIONAL & IMPLEMENTATION ISSUES

13.1 Historical Perspective

Pavement management emerged in the mid seventies *(1)* predominantly as computerized systems which were designed to provide answers to agencies responsible for the task of selecting pavement rehabilitation treatments and timings for their roadway networks. The philosophies of pavement management were accepted immediately by many agencies nationwide. Following this acceptance, many State agencies, such as Arizona and Washington, began the development and implementation of pavement management systems for use in their Highway Departments.

Because pavement management was such a new concept, no standards were available to the agencies who were the early developers of these systems. The earliest emphasis leaned in the direction of optimization of multi-year programs, so Operations Research input heavily influenced their development. The result was very sophisticated systems, which relied on linear programming and Markovian probabilities to select optimal strategies for given budget parameters.

What started as a pragmatic tool quickly shifted into the hands of researchers and educators who explored and promoted the components of pavement management as a high-level technical exercise. Increasing technical sophistication was preferred in all new systems being developed and pavement management fell into the realm of technical elegance beyond the limits most users could understand. The end result of this developmental direction was reliance on pavement management systems as *"black boxes"* which selected and scheduled projects, but had few practitioners or proponents who actually understood the decisions being made by the systems.

By the late 1970s, more and more states were buying into the concept of pavement management, and were buying systems which utilized the technically complicated methodologies being developed. To a large number of potential users, these systems were the only ones available, and without giving much thought as to what a pavement management system should do, they began their implementations.

Within the next five years, users began to be disenchanted with these elaborate systems which they had purchased. Great sums of money had been devoted to the development of these systems which were developed with various levels of sophistication and varying degrees of success. The words "pavement management" were earning negative connotations and the entire concept appeared to be little more than a dying fad.

The Second North American conference proceedings clearly emphasize the importance of Institutional Issues, which can make or break the success of a system within an organization. It was at this point that the interest in "Institutional Issues" began as we know it today.

During the 1980's several activities served to advance PMS. They were the First and Second North American Conferences on pavement management held in Toronto, Canada. The Federal Highway Administration (FHWA) established a policy on pavement management and issued a mandate that all State Highway Agencies would have an operational system by January 1997 (although the mandate was rescinded in 1995). Other activities, which emerged in the last several years, include the development of an AASHTO Task Force on Pavement Management, the issuance of AASHTO Guidelines for PMS, an Advanced Course on Pavement Management and various other courses on pavement management, and an ASTM Subcommittee on Pavement Management Technologies. In addition, the Transportation Research Board (TRB), Committee A2B01 on Pavement Management started to emerge as more of an influential body on the future directions of pavement management than ever before.

13.2 Institutional Issues

In order for pavement management systems to be successfully implemented in any organization, it is important that institutional factors be seriously considered along with the technical components of the system. An excellent overview of institutional issues has been prepared by Smith and Hall *(2)*, and much of the following section has been excerpted from this paper.

There are many barriers to adoption, implementation and effective use of pavement management systems *(2,3)*. In the early years of PMS implementation and development, some of the most important barriers were technical; the PMS concept was not well-developed and the analysis techniques required considerable research to find those that were most helpful. However, over the last several years, the microcomputer revolution has provided greater access to computers and created a more friendly computational environment. The state-of-the-art in PMS analysis techniques has advanced to such a level that many of the technical problems have been addressed, or the approaches to solving them have been identified. Currently, the most difficult problems are related to the people and institutions that must adopt and use the PMS.

All problems have not been completely solved, and there is still a need for improving existing and developing new pavement management data collection techniques, analysis procedures, and decision support software. However, even in the early days of pavement management, there was a recognition that institutional problems could have an influence on implementation and use of pavement management systems *(4,5)*. Since then there has been an increase in interest in this area *(2,3,6)*. Also, there has been a recognition that PMS should be viewed in terms of information management systems in general *(10)*.

These problems may not always be immediately apparent, especially if the PMS has been mandated. In this situation, these so-called "people" problems can lead to the appearance of PMS adoption and implementation from the perspective of an outsider, but they can prevent the effective use of the PMS in the actual decision making. The people problems can be some of the most difficult to address because they can show up as issues in so many places and can reappear as barriers after the issues appear to have been addressed. Sometimes it only takes one person in a critical position to prevent adoption or effective use of pavement management. People problems also constantly change as personnel at all levels enter and leave an organization.

It is the intent of this module to introduce and discuss the institutional issues which are most important to the success of a pavement management system; in particular, organizational and information issues. Finally, guidelines and methodologies, which have been used to address these issues in the pavement management implementation process, will also be presented.

Institutional issues include people, organization, and communication situations that inhibit the adoption of a PMS. These are sometimes called barriers, although the term "barrier"is considered too severe by some people. A barrier can generally be described as a barricade, obstruction, or anything that prevents advance. Barriers can limit, obstruct, or prevent PMS adoption, implementation, or effective use. Not all institutional issues are true barriers. Many of them just require a different approach than if the PMS was adopted by an individual. There are several different types of issues and barriers that can affect PMS implementation. Many of the most troublesome are organizational or people related. Some of these people-related barriers are built into the organizations into which the PMS must be integrated. Others are attitudes of individuals within the organization that must be addressed.

The institutional issues and barriers can be loosely grouped into three classes; barriers related to:

- People
- Organization
- Development & implementation of PMS

The following sections describe several issues and barriers encountered in pavement management implementation efforts that have been placed in these three groups. It is helpful to think of them in these groups to try to develop methods to address them; however, it is apparent that some fall in more than one class. Any one of these may prevent implementation or limit use of PMS, but more than one are often encountered simultaneously.

13.3 People Issues and Barriers

This is related to the personalities and interpersonal relationships of individuals in an organization. Barriers result from personnel conflicts, inappropriate competition, and communication problems.

These problems may not always be immediately apparent, especially if the PMS has been mandated. In this case, an outsider may perceive a successful PMS adoption and implementation, but internally, agency staff can prevent the effective use of the PMS in the actual decision making. The people problems can be some of the most difficult to address because they can show up as issues in so many places and can reappear as barriers after the issues appear to have been addressed. Sometimes it only takes one person in a critical position to prevent adoption or effective use of pavement management. People problems also constantly change as personnel at all levels enter and leave an organization.

Turf Protection: A PMS provides information and analysis procedures that often cross several formal and informal lines of authority and communication within an organization. It provides information on planning for funding needs, programming and selecting sections of pavement for both maintenance and rehabilitation, and determining the impact of funding decisions on the future condition of the network and future funding needs.

Information is power in an organization, and access to information may influence who has the formal authority or informal power to make decisions. This often affects not only the decisions currently being made by planning, maintenance, design, operations, and administrative groups within a single organization, but it may also affect who makes those decisions in the future. When a PMS is implemented in an existing or newly formed group of the organization, the remaining groups within the organization often feel threatened by the new power of the PMS operating group, especially if the PMS group appears to be preparing to make decisions for which the other groups were previously responsible. They may resist implementation of a PMS to prevent a perceived loss of power.

Fear Of Exposure: Pavement management systems provide structured information that often is not widely available prior to the adoption and implementation of a PMS. Those who have been making decisions with less than complete information may resist implementation of a PMS because they fear that the PMS will show that their decisions were incorrect or less accurate than they had stated. They are afraid of possible censure or ridicule by their superiors or others in the organization who now have ready access to pavement information.

Place of Development: A few personnel may refuse to use anything that was not thought of or developed within the agency: "if it wasn't developed here, it can't be any good." Because of this approach, an excessive amount of money may be spent in developing a pavement management component when an existing process could be adopted with a few relatively inexpensive modifications. There is a balance needed between standard pavement management components and agency-specific needs. It is true that almost every highway and public works agency is somewhat differently organized than the others; however, they all have similar management needs and requirements. Some customization is necessary in almost any implementation. However, some of the basic elements of pavement management are similar for similar-sized agencies. The components from one agency can often be modified to allow use in another agency at far less cost than developing a new one.

Resistance to Change: Some people just do not want to change. Some of the other issues just described may be a part of the reasons they do not want to change, but some people just do not want to spend the effort needed to reshape their thinking, decision-making process, and work habits. They will set up barriers because they prefer to keep everything the way it is until they retire. They find all kinds of excuses for not changing and will generally only change when they are forced.

13.4 Organizational Issues and Barriers

A number of conditions and situations in any organization can make change difficult or at times nearly impossible. Many are issues that must be addressed during implementation to keep them from developing into barriers to effective use. The following gives some of the most common situations.

Size Of Organization: Some agencies consist of a single public works director with a few employees all working out of a single office. Other agencies have thousands of employees involved with pavement planning, programming, design, construction, maintenance, rehabilitation, and reconstruction spread throughout several functional departments and regional districts. The staff in an agency must be educated in the purpose of pavement and trained in the effective use of the pavement management procedures. Larger agencies require more effort to get the information and training to all of those that will be affected simply because there are more people who can have an impact on adoption, implementation, and especially effective use of pavement management. A large agency presents more opportunities for pavement management use to be undermined by those informal leaders in the agency who do not support the pavement management approach.

Organizational Structure: Effective pavement management decisions cross the boundaries of many traditional divisions within most highway and public works agencies. The structure of the organization can have a significant impact on the effective use of pavement management. Some organizations encourage intercommunication among the various central office functional departments and the regional or field groups. Others require that communications go up the chain before they cross areas of responsibility. The lack of effective direct communication among pavement management users can have a detrimental effect on implementation and effective use of pavement management.

Agencies can have several different types of structure. Some agencies have organizational structures that were developed when constructing new facilities was their primary activity. In many of those agencies, maintenance received the lowest priority for staffing and funding. As the need to maintain, rehabilitate, and retrofit the existing pavement network became more important, there was no realignment in the structure of the agency to better address these functions. If the structure of the agency does not match the functions that they must fulfill, there will not be an adequate allocation of resources to address the problems that the agency must face. When this occurs, implementation and effective use of pavement management will be more difficult.

Some agencies have centralized decision-making processes. In those agencies, the subdivisions, such as districts or maintenance areas, are responsible for effective implementation of the program developed by the central office. In other agencies, the central office allocates funds to each subdivision, and the subdivision then determines how to spend that money. Decentralized organizations require a different type of decision support outputs for pavement management than for centralized organizations. In decentralized programs, all of the decision makers in the subdivisions must be convinced that effective pavement management is beneficial to them before it will be effectively used.

ORGANIZATIONAL LEVEL: Since a PMS provides new information affecting many major operating units within the organization, new communication channels, both formal and informal, must often be established. When the PMS operating unit it buried deep within the organizational structure, it is difficult for the person responsible for the PMS to communicate and have access to all of those affected by the implementation of the system. Many times, the PMS engineer or manager is relegated to communicating with those on the same organizational level because of protocol and tradition within the organization. Those at the same level as the PMS engineer or manager in other operating units are far enough down the organizational hierarchy that they may have little impact on the actual decision-making process. This may result in the development of new informal communication channels; however, it may also hinder the full implementation and use of the PMS because the real decision makers are neither getting nor using the information prepared by the lower operator in another unit.

PAST MANAGEMENT AND DECISION-MAKING PRACTICES: The effective implementation and use of PMS is affected by past management and decision-making practices in an agency. Some agencies have developed good management practices even though they do not have pavement management decision support software and formalized inspections. For them, the conversion to a structured PMS is a natural evolution of management practices. Other agencies only react to the latest emergency and consider planning to be an exercise in futility. It is difficult to implement a structured management approach adopted in those organizations because planning and programming are foreign concepts to them.

Several types of decision-making processes are used to reach a decision in different agencies and sometimes within different groups of the same agency. These may include:

- Optional decisions: choices to adopt or reject are made by an individual independent of the other members of the agency;
- Collective decisions: choices are made by consensus of the members of the agency;
- Authoritative decisions: choices are made by relatively few in the system who have the power, status, or technical expertise; and
- Combination decisions: various elements of the choices may be made by some combination of the processes described earlier.

The type of decision making in the agency has an impact on the way in which the implementation process must be formulated.

ORGANIZATIONAL STABILITY: Some agencies have a more stable structure than others. Some practically never change, and changes that do happen occur in small, incremental steps. Other agencies experience frequent and radical changes in staffing, structure, and management on a regular basis. A more stable structure allows use of a more complex decision support system.

PLANNING HORIZONS: Some agencies basically plan for a single year at a time. They determine what pavement sections need work in the fall, put together a program in the Winter, get it approved in the Spring, and complete the work in the summer. Others must plan work for 4 to 5 years in advance. This is especially true for complex projects in major metropolitan areas and high-volume highways in remote areas where the work must be coordinated with other activities such as bridges and utilities. The one-year horizon may allow implementation and use of a simple PMS that addresses and priority ranks current needs. Those with longer planning horizons need a method to predict conditions in the future.

CONSTRAINTS ON SELECTION OF PROJECTS: In local agencies, the selection of a project for treatment may be constrained by some other activity on the street such as planned sewer repair in the near future. In complex highway projects, funds may be allocated to a single project for several years in order to complete the work that must be phased. In some cases, funding categories, political commitments, and management decisions constrain the work to specific geographic areas, certain types of work, or even specific projects. This requires that the PMS be flexible enough to allow this information to be entered into the analysis and decision-making process and that committed projects be identified without being classified as being in need of additional work.

FIXED FACILITIES AND PROCESS: Some agencies have invested resources in a particular computer system, a location referencing system, a specific data collection process, an existing database manager, or a spatial database that constrains the decisions that can be made in the development, selection, implementation, and use of pavement management components. The PMS must make use of these existing facilities such as information systems infrastructure because of prior management decisions and resource allocations.

RESOURCES: Pavement management cannot be developed, implemented, or used effectively if resources are not available. This includes both the resources for those responsible for the PMS and funds for implementing the programs developed through the effective use of a PMS.

Those responsible for the development, implementation, and use of a PMS must have funds and resources to complete those activities. Larger-size organizations may find this easier than smaller agencies, because in larger agencies it is often easier to find some resources to allocate to pavement management development and implementation than in a small local agency; however, it is more difficult to coordinate the activities on an agency-wide basis. In most small to moderate-size local agencies, funds are often difficult to allocate to pavement management and pavement management is only one of several activities for which the manager is responsible. Some agencies have much more personnel resources than funds. Others can contract for work easier than they can hire staff. This constrains the resources available to support pavement management development, implementation, and continued use.

Effective pavement management requires the application of treatments at the most appropriate time in the life of a pavement to provide the most cost-effective pavement network. If an agency has a backlog of funding needs and pavements in extremely poor condition, much of the funds available may have to be spent on stopgap type maintenance to reduce the liability exposure of the agency. This can prevent the effective use of PMS-supported decisions to improve the condition of the network unless the PMS is structured to support backlog analysis and show the impact of this type of fund allocation on funding needs. If adequate funds are not allocated to apply preventive maintenance to good pavements and gradually reduce the backlog, a PMS cannot improve the situation.

One-Person Show: Several agencies have invested their pavement management knowledge experience in one or two people in the organization. The PMS positions often are at a relatively low pay level, but they are often filled with young, bright individuals with skills such as computer expertise that are in high demand. These talented individuals often only stay for a limited time. When a promotion, transfer, or job change removes that person from responsibility for pavement management, if often takes several weeks to several months to replace the person. By the time the position is filled, the pavement management knowledge from the preceding PMS manager is often lost. The new person must start over on much of the system. Some smaller agencies have abandoned their PMS efforts when this key individual left. This problem is one of the most troublesome because it is so difficult to address. It is more prevalent in smaller agencies, but it often occurs even in larger local and state agencies.

Cross training is often suggested as the solution. However, all staff members in practically every highway and public works agency have more work duties than they can effectively complete. They must allocate time on the basis of issues of immediate importance. Cross training is never the most important activity until the responsible person leaves–and then it is too late.

Competing Fund Needs: Almost every agency has more funding needs than resources, and there are always many competing funding needs. In some agencies, pavement funding needs must compete for funds with human services, population protection, and all other needs in the governing agency. In other agencies, certain funds are dedicated to transportation needs, and the pavements compete with other highway or transportation needs. Often funds are allocated to the element that has the highest visibility. Those who have spent considerable energies to adopt, develop, and implement a PMS only to see the results ignored because other needs are the current hot item, often become discouraged and discontinue using the PMS. This problem is related to the availability of resources, and it has an impact on the type of reports and information the PMS must produce to support fund requests.

13.5 System Design, Development, or Selection

Although many of the hardware and management support issues should have been resolved in development, there are many options available. The following describe some of the problems that can occur from selection of an inappropriate system.

Matched To Agency Needs: The most important step in selecting and implementing a PMS is selecting one that matches the agency's needs. PMS decision support products can provide recommended programs for pavement maintenance, rehabilitation, and reconstruction. They can also assist in providing support for funding requests. Some agencies have selected and implemented a PMS to justify budget requests only to find that the software only provided assistance in selecting sections needing maintenance and rehabilitation. They then discontinued the use of the software or used pavement management at a lower level than could have been provided by comprehensive decision support software. In other cases, when the agency tried to evaluate the PMS software-generated recommendations to prepare a final program, they found that the pavement sections, cost units, and treatments used in the decision support software did not match their management process. The manual effort to make the PMS software-generated recommendations match their normal management process was so massive that the system was abandoned.

A PMS can use a simple method to get relatively broad information on the condition of the pavement, or it can use an extensive survey to obtain detailed information about each section of pavement in the network. Each of these has advantages and limitations. Several agencies have discontinued use of a PMS because it cost too much money to keep the data current.

It is imperative that the selected PMS provide the decision-support required by the agency. It is also imperative that the resources required to use the PMS effectively are not greater than those that the agency can realistically allocate to that effort.

Complexity: In some cases, the PMS decision support products have been so complex, or poorly documented, that the user could not understand the concepts used in the system and could not explain them to others. When those responsible for using the PMS took the recommendations to management, they could not explain the basis for programming specific streets for rehabilitation or the justification for selecting sections for preventive maintenance. They could neither explain the concepts on which fund request were made nor show the impact of different alternatives suggested by management.

The concepts included in the PMS must be simple enough for those who must use the PMS every day to explain them to their supervisors and funding authorities. The actual computer programs can be extremely complex as long as the concepts can be easily explained and simple problems illustrating these concepts can be analyzed with the software.

"Black Box": The black-box approach to PMS tries to get the user to place his or her trust in some magic system or program. The PMS software is considered a black box when it provides recommendations, but the rationale behind the recommendations is not known. In some cases, proprietary systems were developed in which the developer purposely refused to describe the programmed analysis procedures. In PMS, many early systems described the computer software as a PMS when in fact PMS is a concept that must be adopted by the entire organization and the software is a decision support tool. Some highway and public works engineers selected pavement management software with the understanding that it would provide all of the decisions needed for maintaining their pavement network. They could proudly point to the output of the program and state, “the computer told me to do it” when questioned about their decisions. However, they often did not know the reasoning behind the computer-generated programs. When the programs could not be carried out as the computer instructed, the systems were often discontinued.

13.6 Methods To Overcome Institutional Problems

Engineers tend to think that if they develop a better device or approach to a problem, it will immediately be used. History shows that the existence of improved systems does not ensure adoption. There is a wide gap between what is known and what is actually used in many fields. *(7)*

There are no magic solutions to people and institutional problems. Major changes in most organizations take considerable time and effort. Changes that affect how decisions are made and the flow of information through an organization are some of the most difficult to implement effectively.*(7)* The following information can be used to address and overcome as many obstacles as possible, minimize the impact of others and identify those that must be bypassed. The discussion is presented in general groups to help define how to approach them, although concepts often cross the boundaries of these groups.

Communication: Several of the people problems described can best be addressed by effective and repeated communication. The proponents for pavement management must take every opportunity to explain pavement management concepts and processes to all that will listen. This includes formal presentations to meetings of the agency, to management, and to the funding authorities. It includes training sessions for all of those that will be directly involved so that they have a thorough understanding of the PMS and they can help pass the information to others. It includes informal discussions with all of those who will be influenced by the adoption and use of PMS.

In a recent survey completed in the San Francisco Bay Area, it was found that communication was one of the main differences between those making most effective use of pavement management products and those making marginal use of them. Those public works agencies that had developed good communications with the city and county managers and city councils and county boards concerning the purpose of pavement management and pavement management procedures were able to use the pavement management procedures effectively in the budget process. Those agencies that had not done an effective job of communicating with higher-level management about the pavement management process generally were not able to make effective use of pavement management products in the budget process. Some of the information that should be included in this communication is described in the following.

PMS Supports Decisions: One of the most difficult barriers to overcome is the organizational inertia that resists change and is allied with the fear of exposure. Communication should include a thorough discussion of what the pavement management decision support system will do and how the users should interact with it. There are those who have a misconception that they can buy some software, collect some data, put both in a computer, and have all the answers they need about pavements. It is extremely important to communicate that pavement management software is decision support software. Pavement management is a *decision-making process* that encompasses all of the decision-makers. A PMS incorporates all of these into a functional operation.

In several instances, pavement management concepts have been misunderstood or misrepresented. Several agencies have come to believe that a PMS will manage their pavements. In fact, the pavement management decision support software is nothing more than a decision support tool. The personnel in the organization are the real management system. They make decisions; the software only provides organized information that is used in the decision-making process. This must be stressed again and again, especially to top management and decision makers. Some agencies are separating the terminology of a PMS from that of a pavement management information system. This helps distinguish the decision making and decision makers who manage pavements from computer programs that provide information in decision support.

Proper communication concerning what should be expected from pavement management decision support systems is used to help resolve turf protection problems. It is extremely important to show that the software packages are prepared to provide assistance and support to an experienced pavement engineer and that they may not provide the final answer.

Show Benefits: People are more willing to take a risk in trying a new approach if the potential benefits far outweigh the potential difficulties. This means the benefits must not only be to the agency but also to those persons who will be directly involved or who may prevent acceptance of full usage of pavement management. Some of the agency benefits include better utilization of funds and more effective justification of fund requests. Some of the personal benefits to those most directly involved include the ability to be more responsive to management, better coordination with other highway facilities, and more involvement in the decision-making process.

Compatibility: Compatibility is the degree to which the PMS is perceived to be consistent with the current management process, existing procedures, political realities of the agency, and agency needs. The more compatible it is, the more likely that the PMS will be adopted and effectively used. This is probably the most important aspect to consider when selecting or developing a PMS. The organizational analysis in the implementation is essential to determine how to make the PMS fit within the organization.

The PMS must support the structure and programming process in the agency. If the agency uses a decentralized decision-making process to decide which sections of pavement are preventive maintenance but rehabilitation decisions are made in a centralized manner, then the PMS must support the districts and central office in each activity. The PMS must reflect the decision-making process rather than forcing the decision process to fit the pavement management decision support products. An attempt to change the agency structure invariably creates additional resistance.

The implementation process must carefully identify the formal and informal structures along with their respective lines of communication. The PMS implementation must carefully consider and develop communication links and decision flows to minimize turf formation and reduce barriers. If maintenance has traditionally had a say in which sections of pavement were selected for repair, the PMS must support this process, even if it is a manual review of recommendations from the pavement management decision support software.

The PMS must support the funding and design cycles of the agency. Some agencies require a lead time of 2 or more years. Some types of projects may take even longer. The PMS must support identification of sections needing work and selection of the most beneficial in the time frame that fits the agency's cycle. The shelf life of designed treatments is relatively short, and the PMS must be able to adjust treatments if they are not applied when first planned.

The PMS must support political and managerial commitments that override the recommendations of the decision support software. Committed projects come into existence for many reasons including advanced planning, and they may consume a large portion of the budget for a given year. In many agencies, projects that are perceived to support economic development are funded before maintenance and rehabilitation. The PMS must allow this, although it should still show the impact of applying the repairs.

The PMS must support the agency in decision making when the financial situation is dismal. Some agencies have such a backlog of needs that it is difficult for them to allocate funds to any pavements except those in the worst condition, and those funds are only stopgap treatments that are seldom cost-effective. This type of situation requires special consideration by the decision support software.

The PMS operational requirements must match the agency's resources. If the PMS requires more staff resources than the agency can support, the agency will discontinue use of the PMS or use it at a minimal level. Collecting and maintaining data can be expensive and overwhelming if not properly planned. Only data that are absolutely needed should be collected, and that data should only be collected when needed.

The decision support software must provide the information needed in the form that is most usable to managers. The content of each report must be developed for the management level for which it is targeted. The level of detail normally decreases at higher management levels. The style of the reports is often as important as the content to get acceptance. Some groups require tables of detailed information, whereas others want to see only summary charts and figures. Failure to produce these for each level can lead to a loss of support and eventual discontinuance.

All organizations are required to answer emergency requests for information for which no standard report has been established. Pavement management data structure and decision support software must provide for interactive custom reports. This allows the user to demonstrate the benefit of the PMS in ways that will gain it instant support from those that must provide those answers.

COMPLEXITY: Complexity is the degree to which the system is perceived to be difficult to understand and use. Ideas that are easier to understand are more likely to be adopted. The system that uses concepts and techniques that are familiar to the managers will be perceived as being less complex.

Minimizing the amount of data that the system uses and the number of steps required to complete a task by the user causes the system to be perceived as less complex. The format of the software interface with the user can have a dramatic impact on perceived complexity of the PMS.

The PMS must fit organizational reality. Software that tries to force the agency to match its decision-making process rather than support the decision-making processes of the agency will almost always be perceived as more complex. Many agencies have already invested heavily in computer hardware, data collection processes, databases, and location referencing systems. The PMS should use the existing systems as much as possible rather than develop new ones. This causes the PMS to appear to be less complex.

One of the most difficult problems to address is the one-person show or champion dependency. This occurs because of the lack of time for training others, but it is also due to the complexity of the PMS. A PMS that is less complex is easier to understand and use. This means that it takes less training to learn how to use it and makes it less champion-dependent.

RELATIVE ADVANTAGE: Relative advantage is the degree to which the structured PMS is perceived to be better than the existing process. The greater the perceived advantage, the more likely it will be adopted and used.

The PMS must show the benefits to the agency and those working in the agency. Each group in the agency and each person that must invest time and effort in PMS implementation and use should be able to see some benefit. The implementation should make a special effort to ensure that all tangible and intangible benefits are identified and documented. This can be monetary benefits, such as the ability to repair more pavements with available funds, or it can be non-monetary benefits such as the ability to answer management questions more objectively. By structuring the PMS to provide quick and accurate answers to the “what if ”questions that are common at budget time, it provides an advantage to the managers by allowing them to be more responsive and knowledgeable.

The PMS should be structured to help secure additional funds for the maintenance, rehabilitation, and reconstruction of pavements. Few agencies have the funds to complete all of the work needed. Most agencies have large backlogs of funding needs, and many agencies must compete for funding with other public needs. This leads to competition for funds within the funding authority with non-transportation needs and within the agency among transportation needs. The pavement management decision support software must provide reports and information in a form to support fund requests in this competitive environment. It must show the economic impact of different alternatives so that funding authorities can see the effects of their decisions. Graphical reports will be especially needed in this effort.

The PMS should provide a comprehensive and balanced analysis of all pavement needs including maintenance, rehabilitation, and reconstruction. This will provide the greatest benefit to the agency and provide support for the widest possible number of users increasing the advantage for each. This will support multiyear plans needed for long-term planning and trade-off analysis.

The PMS should provide multi-disciplined decision support to all of the various groups in the organization that must deal with pavements. These include management, subdivisions such as districts or maintenance areas, planning, programming, construction, design, and maintenance. This will provide the greatest relative advantage by addressing the needs of more groups and individuals within the agency.

Adaptability: Adaptability is the degree to which the PMS can be modified to meet individual differences in needs. Decision support needs can change over time, and the ability to modify the PMS decision support system to meet these changes is desirable, but the PMS must allow changes without making the system unduly complex.

Although it seems that organizations may never change, internally there are often significant changes when individual managers change. Retirements and turnover are currently creating considerable changes in managers. The PMS must be capable of adapting to the changes in reports and formats but withstand changes to the substance of the process unless the structure is making a permanent change that requires modification of the decision support process. Modular programming, simplicity in design, and standard data base structures can all assist in providing adaptability without becoming too complex.

The PMS should be able to meet special needs. Planning and programming for maintenance, rehabilitation, reconstruction, and even abandonment may require special consideration and analysis in major urban areas and environmentally sensitive areas.

The PMS should coordinate with other road and street improvements. In state agencies, congestion, safety, bridge, public transportation, and inter-modal management systems were included in the original ISTEA mandate. In local agencies, many pavements have several utilities beneath the surface. The responsible agencies must make the best use of limited funds for all activities. These systems can interact at several levels including conflict analysis, needs analysis, and fund allocation. Establishing these links will lead to better transportation systems.

The PMS adopted must accommodate technological changes. New data collection techniques are under development that could reduce the cost of data collection and at least reduce the exposure of workers to accidents. Computer hardware keeps getting faster and more powerful. New, more realistic optimization techniques are being developed and tried. New pavement maintenance and rehabilitation treatments are being used. The PMS must be capable of incorporating these and other changes that will occur. Developing the decision support software in modular form and using standard procedures as much as possible will allow more efficient updating.

Support From Upper Level Management: Many “people” barriers such as turf protection and fear of exposure can be overcome only with support from upper-level management and a long-term commitment to using the PMS. Upper management may be able to force the formal communication channels to function, but sometimes few informal channels that bypass impediments may have to be developed. This is the same process that must be used to address those who intentionally block communication channels.

Management must establish long-term financial support for the maintenance and operation of the PMS if it is to be used effectively. This may include developing a special pavement management group within larger organizations with their own operating budget.

TRAINING: Training is vital to implementation and effective use of a PMS. The training must address all of those who will be affected by the PMS. It must be cyclic and continue indefinitely.

In the hands of someone unfamiliar with pavements who follows the PMS recommendations blindly, erroneous results can be produced. This can be alleviated by providing training for several levels of PMS efforts in an agency, which includes training and seminars on proper use of maintenance treatments, quality assurance, and specifications for maintenance and rehabilitation treatments. This approach creates an atmosphere in which the PMS can be discussed in the context of how it helps make decisions about treatment selection and timing, so that it appears much less threatening to those who have made these decisions in the past.

Complexity is relative to the sophistication of the users and can be decreased by communication, on-call assistance, and training. Comprehensive documentation of the software and the operating concepts also help reduce the appearance of complexity.

Training should be conducted at several times and at several levels. When the PMS is being implemented, training should be conducted on the principles of the PMS, how to interact with the decision support software, how to prepare reports for different management levels, how to use the results to support budget requests, and how to compete for funds. The training should be directed initially at those most directly involved.

Some types of training are more formal than others. Classroom instruction can be used to discuss pavement management principles, but hands-on training is more effective for teaching interaction with the software and hardware. Training in how to generate reports and develop budget requests can best be completed in a hands-on fashion or by producing examples.

Upper management, funding authorities, and the public will need training. This will often be bite-size training presented less formally for upper management and funding authorities. Public training will often be in the form of public information brochures and releases to the press.

Training should be directed at the areas of greatest resistance. When a particular manager or group within the organization appears to be blocking acceptance or full use, training should be directed at that point. Some of it can be formal, but much of it will need to be informal demonstrations.

Just when it appears that everyone is trained, there will be staff changes. Inspectors that work in data collection for only a few weeks each must be retrained before the beginning of the next data collection cycle. Training will need to be repeated periodically for those activities. As enhancements are made to the data collection procedures and decision support software, new training will be needed. Experience shows that the PMS personnel need training before they can be effective users; however, after they have been using the PMS, the same training repeated is even more effective.

Outside Support: Some outside agencies can assist pavement agencies in adopting an effective implementation of PMS. The FHWA and National Highway Institute offer various training courses and workshops on PMS, such as this one. Regional and national meetings, workshops and conferences are also excellent sources of information; such as the recent National PMS Workshop in New Orleans, LA (July 1997). The Local Transportation Assistance Program (LTAP) Technology Transfer (T^2) Centers often have staff members with PMS expertise that can provide assistance to local and regional agencies. These centers also call on members of the local academic community with PMS expertise. Several consulting engineer firms have developed PMS expertise. The FHWA work cited here *(1)* contains a list of consulting organizations with PMS experience. Regional FHWA offices, LTAP, T^2 Centers, and local universities may also be able to help identify firms with PMS experience in the local area.

The "one-person show" problem has been countered in a few agencies in the United States and several international agencies by contracting with consulting firms to act as the pavement manager. The consultant helped implement the PMS in the agency, and then the firm contracted to provide PMS expertise to the agency by keeping the PMS data current, identifying pavements needing work, selecting the primary candidates for work, and even identifying the treatments to be used. Other agencies have contracted for specific expertise to be provided by the consulting firm. Some agencies lack adequate personnel to collect the data needed for initial and continuing surveys, and several firms have assisted them in PMS data collection. This approach effectively transfers some of the expertise problem to the consulting firm; however, the agency must still maintain some level of expertise to be able to use, present, and defend the recommendations provided by the consultant.

13.7 Implementation Concepts & Guidelines

Most implementation guidelines are prepared under the assumption that the decision to implement pavement management has been made *(8)*. They generally do not address the problems of an individual in an organization who must convince the management structure that pavement management is something that should be adopted and implemented. In addition, many guidelines stop after the pavement management system has been adopted, pavements inspected, and information is in the computerized system.

In Smith's *(8)* paper, he addresses five phases of pavement management adoption and implementation that covers the full range of implementation. These five phases may by summarized as:

1. Decide if pavement management is needed
2. Obtain agency support
3. Select PMS
4. Implement PMS
5. Operate the PMS effectively

When the fifth phase is finished, implementation can be considered complete, because the pavement management process becomes the standard method of managing the pavement system in the agency.

Much of the information contained in this section is located in Reference *8*.

Step 1- Decide If Pavement Management Is Needed: This phase is directed at the potential pavement management "*champion*" in an agency. A "champion" is a person, or small group of advocates, in the agency that recognizes the need for and benefits of pavement management in the agency and works to get it adopted and implemented. The champion must first be convinced that pavement management concepts should be adopted, and then the champion must convince the agency to adopt pavement management *(9)*. The champion may be responding to, and have the support of, a counterpart champion in an influential external agency. The following is a series of steps the champion must generally complete to reach a positive decision about pavement management adoption and implementation.

Recognize Need: The champion in the agency recognizes a need to change or enhance the manner in which pavement design, maintenance and rehabilitation planning and programming are conducted. This can occur through a perceived need to improve the process when the person encounters a problem which is difficult or impossible to address with the current system. It can occur when the person learns about pavement management and its capabilities from other personnel, technical publications, professional association meetings, or other professionals. It can be identified by members of the agency administration as a management objective they perceive as needed in the agency. It can also occur through legislative or other outside agency mandates to use the process.

Obtaining PMS Knowledge: The champion must have the knowledge necessary to decide if pavement management will be good for the agency. Knowledge of the principles of pavement management are important at this stage in order to insure that the pavement management process is relevant to the situation in the agency.

The "how-to knowledge" is critical at this point. The champion must determine what information is desired by potential users, how the pavement management procedures will be used, what answers must be provided, how much it will cost to implement, the benefits provided, and what changes will be required in the existing agency. The champion must be able to compare advantages and disadvantages of the systematic pavement management procedures with current procedures.

New approaches to public works management create uncertainty in those affected about how their jobs, authority, and responsibility will be modified. The champion must have enough information to reduce that uncertainty to the point where he/she believes that adoption of the pavement management is appropriate for the agency. Demonstrations of an operating pavement management system, case studies, formal training sessions, and discussions with peers using pavement management are an effective means of obtaining this information.

Decide to Implement PMS: The agency champion decides to actively pursue adoption of pavement management in the organization or to reject it. Documented information on the benefits and cost associated with pavement management are important at this stage. How much it will cost to implement, the benefits it will provide, and what changes will be required in the existing agency are very important at this point. Implementation efforts by other agencies using pavement management can be used to demonstrate the costs and effects. Many times, this decision point is not a single instant in time. Rather, the decision is reached over a period of time. More information is obtained in the previous step.

Develop Alliances: Pavement management usually crosses several traditional divisions of authority within an agency. This includes those departments responsible for pavement design, maintenance, rehabilitation, planning, programming, and construction. Pavement management systems are also only one of several infrastructure management systems in most agencies and so must interface and harmonize with other systems. Pavement management normally crosses functional lines and their associated management processes of design, utilities, traffic control, traffic capacity planning, budgeting, information management, maintenance management, work management, and others. The information management aspect is particularly important because it has a central role for all management processes. Members of each agency and sub-agency, which must interact with the pavement management process, may be able to prevent or retard adoption. A very important step needed in adopting innovations within an agency is the development of an alliance of key individuals in each affected department that would like to see pavement management adopted. They should generally formulate an initial set of goals they hope to achieve with pavement management.

Getting Pavement Management on the Agenda: In most agencies, innovations which affect the management efforts of several departments, such as pavement management, must be approved by at least the agency director and often by elected officials. These officials must be convinced that the current process needs to be changed and that pavement management can provide the needed help. Before they will be convinced, pavement management must become a part of the agenda, formal or informal, from which the decision makers work. Getting pavement management on the agenda focuses the attention and energy of the agency on it as a topic to be addressed. This is many times the most difficult step and may require considerable effort and time by the pavement management champion. The alliance of department managers with established preliminary goals is helpful, and sometime absolutely essential, in getting pavement management on the agenda for discussion with the leaders who must approve changes to the management process and structure.

Step 2 - Obtain Agency Support: In this phase the agency management commits to implementing pavement management. One of several decision making processes are normally used to reach the decision. The type of process used depends on the type of agency, organizational structure, and personalities of the managers in the agency. Normal decision making processes include:

- *optional decision* - choices to adopt or reject are made by an individual independent of the other members of the agency;
- *collective decision* - choices are made by consensus of the members of the agency;
- *authoritative decision* - choices are made by a few people in the system who have the power, status, or technical expertise; and
- *combination decisions* - various elements of the choices may be made by some combination of the processes described above.

In many agencies, there is some combination of all of the different decision making types. The decision to implement pavement management may be authoritative because it is forced on the agency by policies of outside agencies or the agency administration. The actual selection of the pavement management system might be based on collective decisions. Some groups within the agency may have the option of being involved or not.

Decisions can also be contingent on previous decisions. A previous investment in expensive data collection equipment may force use of that equipment in the pavement management processes being adopted or developed. Decisions may also be conditional. For instance, the decision may include a provision that pavement management will be implemented for a small portion of the pavement network on a trial basis. At the end of the trial implementation, an evaluation will be made to determine whether to continue, modify the selected approach and try again, or discontinue implementation.

In this phase, the pavement management champion must convince the agency management that pavement management is appropriate for the agency. The method of decision making within the agency will have an impact on how the pavement management champion organizes the information, gets the topic on the agenda (formal or informal) and develops support for the pavement management decision, but it has little impact on the information needed. The champion must guide the agency through the same steps that the champion went through to make the decision to adopt pavement management.

Persuade Agency: The champion must have adequate knowledge to demonstrate that the pavement management approach is better for the agency than the current management approach. Knowledge of the principles of pavement management are important at this time so the champion can explain the concepts to the decision makers in the agency. The pavement management champion must show that there are problems which are difficult, or impossible, to address with the current system and persuade them that pavement management can assist the agency in achieving their management objectives.

The "how-to knowledge" is critical at this point to present the advantages and disadvantages of pavement management processes compared to the current procedures. The champion must know what information is needed, how the system is used, what answers it can provide, how much it will cost to implement, the benefits it will provide, and what changes will be required in the existing agency. All new management approaches create uncertainty about expected consequences, and the champion must have enough information to reduce that uncertainty to the point where the agency decision makers can see that the pavement management process would be helpful to the agency. Demonstrations of operating pavement management processes, case studies, formal training sessions and presentations by other agencies using pavement management are effective means of providing this information.

Agency Decides: The agency's decision makers decide to adopt (or reject) formalized pavement management for the agency. This is the culmination of the persuasion stage described above. In some instances, the decision is made to reject, but no such decision is final in most pavement agencies. The decision to reject forces the champion to start over with the collection of information and other steps described above. The decision can be conditional i.e., a trial implementation now with decision to proceed with the final or full implementation made at a later time.

Form a Steering Committee: A steering committee should be formed of upper level management personnel and possibly include elected officials. All departments affected by or involved in the implementation of pavement management should be represented on this committee. This committee should provide the support needed to facilitate the changes created by the pavement management process crossing traditional lines of authority. They should prepare goals for the implementation committee or champion and provide the resources to achieve the goals. Although the committee meetings may be time consuming, it is essential to have the interaction of all affected groups to get their "buy in" of the pavement management support software and procedures selected.

Gain Commitment for Funding: Real commitment is achieved in most agencies when funding is committed. The steering committee should insure that adequate funding to support pavement management implementation has been allocated. The available funds may control the rate at which the implementation can proceed. Funding can be allocated incrementally for a pilot implementation and staged implementation for the remainder of the network.

Form an Implementation Group: In small agencies the implementation group may be a single person, hopefully the pavement management champion. In larger agencies, this can include the formation of a separate pavement management work group. The group must convert the goals prepared by the steering committee into a work plan which details the tasks and resources required to adopt and implement pavement management in the agency. This group will be responsible for the day-to-day efforts throughout the implementation period. It should be responsible for completing the remaining steps described below; however, this group must work closely with the implementation steering committee. The working group should include representation from all of the major user groups. However, one person must be in charge and have authority to make day-to-day decisions.

Testing Pavement Management Processes: In this phase, the decision to adopt, or at least complete a trial implementation of, pavement management has been reached by the agency. The pavement management approach, the software and data collection processes have not been selected. This phase normally includes matching and restructuring processes. The agency must find the pavement management system components, data collection methods, pavement management software, and management procedures that meet the needs and constraints of the agency. In many cases this may require adopting existing components and processes and modifying them to meet special needs of the agency. This is the first time within these guidelines when pavement management is actually used within the agency.

Step 3 - Organizational Analysis: The implementation group compares the pavement management process to the existing process to determine how it can be used to facilitate the pavement decisions or alleviate the perceived problem. They must review the existing organization, methods and procedures to determine how the pavement management process will support decision making within the agency. The decision support provided by the adopted pavement management process must match the needs of agency. Location of the person or staff responsible for pavement management in the agency is often a difficult decision. A pavement management system that matches the methods and procedures currently used by the agency has a much better chance of being fully adopted and used than one that requires major changes in the organizational lines of communication, chain of authority, data collection procedures, and data storage processes. However, the opportunity to improve the efficiency of management within the organization should still be considered, since duplication of functions like data collection can be avoided. Changes in organizational structure, processes or lines of communications should be developed carefully in the context of all pavement management processes and should be planned rather than allowed to happen in isolation.

This should include a review of the agency structure, the communication flow, data collection processes, existing data bases, other affected infrastructure systems, data flows and decision making processes. The implementation group must have the information to demonstrate the problem and show how available pavement management support software and processes provide the needed solutions. Accurate, reliable information on the costs and benefits of the various pavement management systems, software and data collection are critical at this time. Generally the implementation group must provide information and show how similar agencies have used the selected procedures, approaches and software. They must demonstrate the relative advantage provided by pavement management systems and the compatibility with existing procedures to reduce the anxiety of others.

Select and Design PMS: This is basically the systems design that must follow organizational analysis. These activities should include selection or development of the decision support software, determination of data to be collected, definition of data collection processes, and decisions about data storage processes. Of special importance are the central and common aspects of information management as they affect data processing and storage. The information management system architecture must be developed considering harmonizing data standards, definitions, and reference systems. The data to be collected, the cycle of data collection and database update must be defined. In this step, basic decisions about the division of effort between network-level and project-level pavement management processes as well as the interface between network and project-level management must be made. This step will determine where the pavement management support software and staff should be located and who will be responsible for insuring that data is collected on a timely basis. It should include development of requirements for training resources and software support. It may also include purchase of hardware and associated software.

This can be time consuming, and it should involve the working group with several reviews by the steering committee. The selection should insure that it is feasible to complete or support the data collection required by the process selected. It should insure that the system addresses all of the network-level questions required by the agency, that it can interface with the desired project-level system, and that it supports the existing management structure of the agency.

Modify Selected Pavement Management Process: Every pavement agency will always see a need to modify any system to make it fit their real or perceived unique situation and problems. Many times the modifications are minor changes to reports and data collection procedures, but they are important to insure acceptance of the pavement management system. Thus, adaptability is important at this time; however, the system must still be perceived to be appropriate and affordable to implement while also being compatible with current management procedures. The systems, processes and methods selected in the previous step are modified to fit the needs of the specific agency.

Prepare Staged Implementation Plan: The implementation should be planned in as much detail as possible, even though it will probably be changed at a later date. This is normally done by the implementation group and approved by the steering committee. It is generally not possible to implement pavement management for a large network in a short time. However, each data collection process, software system, report, and data storage method must be tried to determine if they match the needs and constraints of the agency. Changes will be needed based on trial use of the software considered and selected. Those changes need to be planned for and identified early to avoid costly revisions. Using a pilot implementation in the phased implementation facilitates these adjustments. It also provides information to permit a more accurate estimate of the time and resources needed to complete implementation.

Staged implementation is also often necessitated by available funds and time. It is important to provide adequate time for the training needed for all of those involved in using pavement management during the implementation. Pavement management is not just software, it is the management process which includes all of the decision makers involved. They generally must make some adjustments to accommodate the new information that will come from the pavement management decision support software. They must be trained to effectively use the information from the pavement management process. Training is generally most effective when real information is available from the agency's own pavement network.

Trial Implementation: The system selection is normally followed by a pilot, or trial implementation. A small percentage of the network is used to test the pavement management system, decision support software, data collection processes, data storage, and other activities. The trial implementation should go through every management step in the pavement management process. This allows the agency to "try-out" the system, and it permits them to identify the elements that require modification to meet agency needs. It also serves as an aid in training the various users of pavement management which should be a major part of the implementation efforts. The costs and results of the system should be thoroughly documented. This helps define the implementation resources and training needed for full implementation. Feedback from pavement management users should be programmed into the implementation process from the start so that they have an investment in the system and are more likely to assist with adoption rather than develop barriers.

Document Results: It is very important to document the findings of the trial implementation based on the goals and work plans established earlier. This will better identify the resources and time needed to complete information. It will help determine if the current plan can be followed or must be modified based on this more complete information. The documentation should include recommendations for modifications for the adopted pavement management system software, data collection processes and continued implementation. The results often must then be presented to the steering committee before implementation continues.

Step 4 - Select PMS: The agency decision makers commit to continue with full implementation, to revise pavement management concepts or to reject pavement management at this time. The agency may decide to repeat a few previous steps because of problems encountered during the pilot implementation prior to continuing into full implementation. Rejection may be a temporary set back or may result in years of delay before pavement management will be considered again. That makes it imperative that every effort be directed at a successful trial implementation.

Documented information on the current and future costs of the selected system are important at this time along with expected benefits. Results of trial implementations must show that the recommended system can provide the support needed by the agency and fit within the agency's constraints. Information from other agencies can be used to help demonstrate the benefits, but costs should come from the pilot or trial implementation within the agency. The steering committee or implementation group should present the results from the steps above to the decision makers and convince them that pavement management processes should be continued through full implementation.

Review the Goals: After the pilot implementation, the original goals developed by the steering committee should be thoroughly reviewed. Based on the organizational analysis and the information gained from the pilot implementation, goals should be revised to match the agency needs to the constraints, especially the available resources needed for full implementation and use. It is particularly important to consider training and support plans in the goals and funding needs at this point.

Review the Implementation Plan: The pavement management implementation group should review the work plans, resource requirements, and time requirements. The implementation group should work from the revised goals using the information learned during the pilot implementation to revise the implementation plan. The pavement management system, the software, and the data collection methods should be thoroughly reviewed. At this point it is possible to make major changes relatively easily; after full implementation, major changes are almost impossible for a number of years.

The revised work plan can still be staged. The staging can be by area, system, or other division that meets the needs of the agency. Training and support plans are of particular importance at this time to insure that all potential users are familiarized with pavement management concepts and how they can interact with the pavement management process. Major changes to software, data collection, or data storage should be planned to allow the implementation to continue while permitting required improvements.

STEP 5 - IMPLEMENT PMS: After the pilot implementation, the pavement management process must be implemented for the remainder of the network. At this same time, needed modifications must be completed. This may require that the agency go back and collect new data, or the same data in a different way, for the pilot network. The steps within this phase should include revision of the system, software and data collection processes, full implementation, and training. This will include the revisions to the software, data collection processes and data storage procedures. It may be relatively simple, or it can include major revisions. This can be completed concurrently with the following step. The implementation will include the most intensive data collection and training activities. Several tasks may run concurrently and implementation can still be staged.

Collect Data: The data collection and inclusion of various elements of the network will often be staged even after pilot implementation. The freeways, primary arterials, or primary runways might be included in the first stage. The next most important set of pavements may be included in the next stage. This would continue until the entire network is included in the implementation. A method to assure the quality of the data collected must be established and in place at this time.

Train Staff: Training should be included as an essential element of each activity. As the scope of pavement management increases and the implementation steps are completed, all of the users and operators involved in pavement management must be trained on pavement management concepts and system usage. This includes those who are seeing new or more complete reports and those who will use the information from the reports to make decisions. This may include a series of meetings with the funding authority to educate them in the new information or form of data which they will receive. The general public should also be included in the training to help them understand how their facilities are being managed.

Step 6 - Operate PMS Effectively: Once the initial data has been collected for the entire network and the first set of reports completed, many consider the system implemented. A true pavement management process is not a one-time condition survey followed by a report. Pavement management is a structured method to make decisions about pavements and requires a long-term commitment to improve management practices. A commitment will be needed to repeat the data collection and analysis activities on a periodic basis in the future. If pavement management is to be effective, it must become a part of the routine management process and affect the decisions being made. The purpose of this phase is to institutionalize the pavement management process within the managing organization.

Match Output to Management Styles and Needs: Considerable effort is often required to educate the upper level managers about the benefits of using pavement management and the reports generated by the pavement management decision support software. No matter how good the earlier investigations are, some of the reports generated by the software will not meet the needs of the upper level managers. Pilot implementation will identify some changes, but many needed changes in reports and formats will only be found when the system starts working in earnest. The pilot implementation should have identified data problems and needs that should have been subsequently corrected. The changes identified at this point are primarily related to report structure, report format and presentation style. These changes will be needed at this point in part because the users will not completely know what they want until they see some of the reports from the system. As they learn to use the information, they will see other ways to use the same information. As new senior personnel use the system, additional requirements will be identified. It is essential that these requirements be met to maintain the credibility of the system. Some senior managers will be reluctant to use the results of the pavement management process if they do not fully understand them and believe in the accuracy of the information. Considerable training on an informal basis is often needed with some senior managers.

Step 7 – Pms In The Organizational Structure: Step 7 - PMS in the Organizational Structure: In order to ensure continuity of PMS development, provision must be made to formalize pavement management into the organizational structure. Although a single champion may have led the development and implementation of pavement management in the organization, pavement management responsibilities must be formally designated to survive inevitable management and personnel changes.

The formal responsibility may become a part time requirement for a single person in small agencies or it may be a formal assignment of duties to several people in several areas for larger, more complex, agencies. The formal organizational arrangement should facilitate development and distribution of information to support the organization's decision making process at upper, middle, and lower management levels.

Of special importance is the assignment of responsibility for data collection, data entry, and maintaining integrity of the data base. Only one assigned person should be responsible for adding and modifying data for which the group is responsible. Access for retrieving, reporting, data analysis and other uses of the data should be made as easy as possible to all interested parties.

Training: Changes and improvements, especially in the reporting system, the data collection processes, and the analysis techniques will continue indefinitely, although at a much reduced rate. Training is needed when changes are made to the systems; however, cyclic training is needed even when changes do not occur.

Training must continue on a repeating cycle. Many pavement management personnel only work with the software and report generation for a few weeks each year, and condition data are normally collected for a short period each year. These individuals need refresher training each year. The responsible staff will experience turn-over, and the new members will need training on a continuing basis.

Adjust and Improve: Pavement management procedures and data collection procedures continue to evolve as technologies advance. Computer capabilities continue to increase which allows more complex analysis and storage of larger data sets. More easily understandable decision support processes are being developed that can replace complex, difficult to understand procedures.

The software system should be modular in form and flexible enough to allow improvements and modifications over time. However, changes made too frequently will frustrate users who feel that once they learn the system, it is changed. Training is essential to assist users in understanding the changes.

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MODULE 14

QUALITY MANAGEMENT

14.1 Module Objectives

This module introduces the fundamental principles of Total Quality and the application of the principles to Pavement Management Systems. Upon completion of this module, the participant will be able to accomplish the following:

- Identify the fundamental principles of Total Quality
- Become familiar with the application of Quality Management in PMS as applied in Massachusetts.

14.2 Introduction to Total Quality

Quality is something consumers expect in the things they buy and the services that are utilized. How is quality defined? How is quality achieved? Since quality is a “good thing”, how can quality be incorporated into the work and products of a PMS?

Quality is the efficiency of a business system to meet external needs *(1)*. In pavement management, the external needs are defined by the users of the roads, i.e. the driving public. External needs are also defined by the providers of funding for development, design, contruction and maintenance of a highway system. In other words, a quality product is defined by the user, not the producer.

In an effort to respond to eternal needs, many businesses have incorporated the practices of Total Quality Management (TQM). Over the years, TQM has taken on many meanings. Some of the generally agreed principles of Total Quality are as follows *(1)*:

- Top management commitment to TQM
- Employee belief in management’s commitment to TQM
- Leadership: executives and managers who see their role as customer advocates, strategic planners, barrier removers, and “walkers of the talk”
- An unending, intense focus on customer’s needs, wants, expectations and requirements, and a commitment to satisfying them
- Decision-making based on data, measurement, and statistical inference, rather than opinions
- A view of process control that embraces reduction of variation, rather than just meeting the specification, to create customer satisfaction
- A commitment to continuous improvement, that is, “if it ain’t broke, improve it”
- Focus on process improvement versus production inspection
- Focus on prevention of problems rather than fixing problems
- An organizational climate based on collaboration and trust instead of competition
- A lean organizational structure which depends on cross-functional teamwork, not vertical organizational hierarchies
- An approach to product/service development which is more concurrent than sequential and uses cross functional groups working as a team
- A view of customers and suppliers as partners, not adversaries
- Management focus on long term results rather than short term profits and schedule

Although the above list may seem more applicable to business and industry, it can also be related to highway agencies, particularly in the implementation and use of pavement management systems.

An example of implementing Total Quality principles to achieve pavement quality is the Massachusetts Pavement Quality Partnership (MassPQP). The following text discusses the motivations for establishing the MassPQP effort, the basic organization of the partnership, and where they are now.

14.3 The Massachusetts Pavement Quality Partnership (MassPQP)

The Massachusetts Pavement Quality Partnership is a joint public/private effort to achieve quality pavements through the application of TQM principles and partnering methods *(2)*.

One of the key factors for driving the state highway agency in Massachusetts into a quality program was the realization that pavement quality was deteriorating. There was a lack of expertise within the design and construction community, whether public or private *(3)*. At the same time, the state was interested in the National Quality Initiative (NQI), so the Massachusetts Highway Department (MHD) began to focus on quality pavement construction and design. One goal was to get pavement management institutionalized into the system. The work effort was strongly supported by the top-level management. This was instrumental in getting the program started. Support came from the commission as well as the state's Chief Engineer.

The goal of the MassPQP is to "establish and maintain high quality pavements in a cost effective manner". In order to achieve this goal, the following five objectives were established:

- Define Quality Pavements in clear and measurable terms
- Assess the existing level of pavement quality in Massachusetts highways
- Develop the primary elements of a long-term "blue print" or MassPQP Strategic Plan
- Recommend further actions necessary for implementation of the MassPQP Strategic Plan
- Provide support, guidance and a "synergistic environment" to front-line workers in the implementation of the MassPQP Strategic Plan

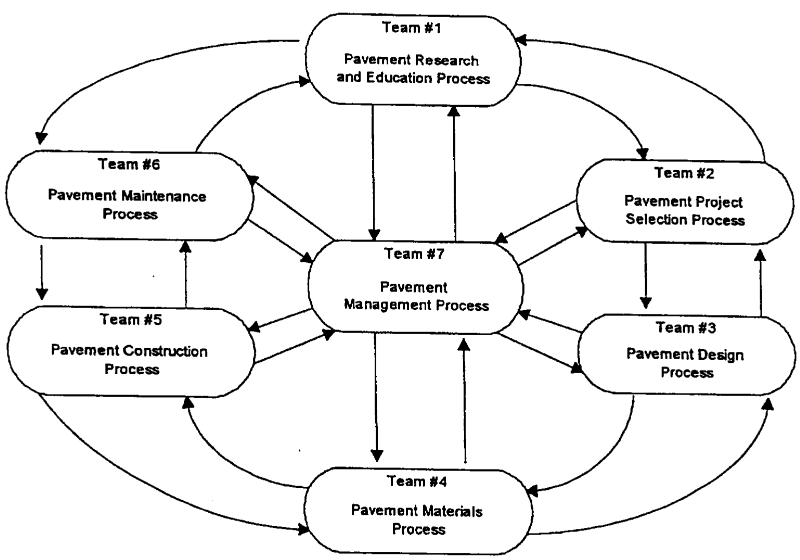
The focus of the MassPQP is to establish a joint public/private partnership to achieve the goal and objectives throughout the application of TQM principles (Continuous Quality Improvement (CQI) process) and partnering methods. The heart of the MassPQP proposal is to create a group of pavement quality "Work Teams" that reflect the relationship of the major functional activities associated with the pavement process.

The seven work teams are as follows:

1. Pavement research and education
2. Pavement project selection
3. Pavement design
4. Pavement materials
5. Pavement construction
6. Pavement maintenance
7. Pavement management

In the MassPQP Stategic Plan, the first six processes form an outer ring to indicate their need for continuous interaction and communication during the pavement life-cycle. Located at the core of these six processes is Pavement Management. This indicates how the Pavement Management Process serves as the nucleus of the MassPQP Pavement Quality Process. In a CQI environment, the Pavement Management Process gathers important input from and provides needed information to each of the other six pavement processes. A diagram of this seven process relationship is shown in Figure 14.1.

Figure 14.1 MassPQP Pavement Quality Process (2)



BUILDING THE PARTNERSHIP: On November 10, 1992, the National Policy on the Quality of Highways was adopted by all of the participating organizations. A primary objective of National Quality Initiative (NQI) was to cascade the approach and overall mission to individual state organizations. Accordingly, the Massachusetts Highway Department (MHD) established the Massachusetts Quality Initiative (MQI).

The MQI is led by a steering committee that developed an initial plan to provide the highway user with the quality products and services they expect. To achieve this effort, MQI initially identified four Quality Initiatives:

- Partnering
- Quality Control/Quality Acceptance (QC/QA)
- Total Quality Management (TQM)
- Value Engineering (VE)

The role of the MQI Steering Committee is to provide overall direction to each of the MHD Quality Initiatives and is comprised of members who represent the FHWA, MHD, Private Industry and Academia. The organizational chart is shown in Figure 14.2. The structure that was defined for the MassPQP is shown in Figure 14.3.

Figure 14.2 MQI Organization Chart (2)

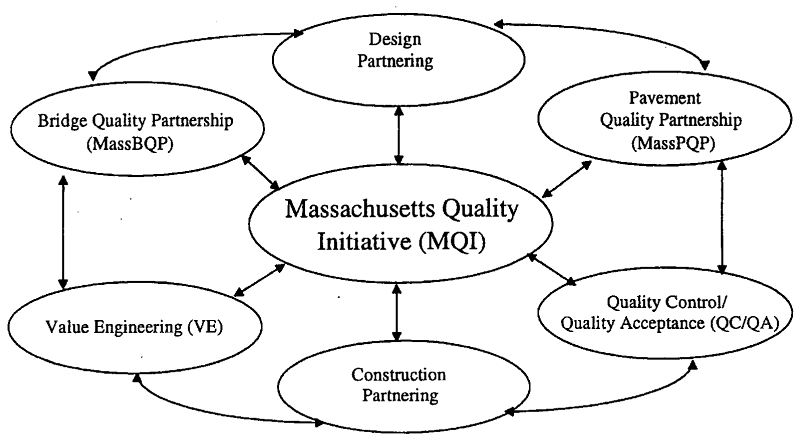
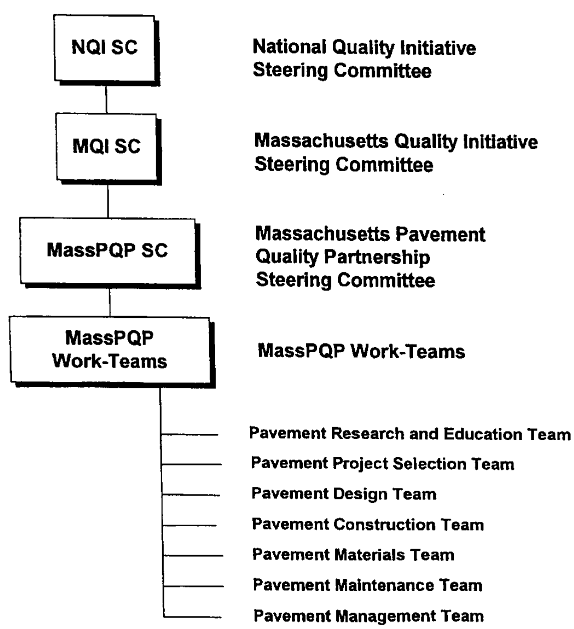


Figure 14.3 Structure of the MassPQP (2)



ACHIEVING THE STRATEGIC PLAN: The approach selected by the MassPQP Steering Committee to develop the initial Strategic Plan was through a series of partnering workshops. The workshops were structured to teach the work team members the TQM and partnering tools necessary to attain the MassPQP objectives. The major workshop accomplishments are summarized as follows:

- The partnership began a process of working together to learn and appply TQM principles for the purpose of imporving pavement quality in Massachusetts.
- Vision Statement, Mission Statement, and Values were developed by the MassPQP work Teams.
- The "Massachusetts Policy on the Quality of Pavements" was drafted and ratified.
- A "quality pavement" was defined.
- The elements necessary to establish a Quality Measuring System were identified.
- Each work Team developed for its respective process:
  a. A *Process Flow Diagram*
  b. A list of prioritized *Process Issues and Improvements*
  c. *Action Plans* for improvement of top Issues
- The output of the workshops was synthesized to produce the Stategic Plan. In MassPQP, the Strategic Plan includes 26 work team action plans to address the top pavement quality issues identifed in the workshop process.
- The work team leaders and the MassPQP Steering Committee developed an implementation plan for the Strategic Plan.

DEFINING AND MEASURING PAVEMENT QUALITY: The MassPQP Steering committee and Work Teams determined that a "quality pavement" might be defined as possessing five quantifiable and measurable "characteristics" as follows:

- Smoothest practical ride
- Safest pavement surface
- Least possible maintenance
- Lowest life-cycle cost
- Most environmentally friendly

These characteristics form the core of the MassPQP's definition of a quality pavement. Each of the five characteristics can be quantified through specific and measurable "criteria". Pavement Quality Management enables the agency to provide a series of baselines against which the condition of the pavement system can be monitored and through which necessary corrective actions can be identified to improve the pavement system. The MassPQP work teams identified draft *Criteria*, *Tools*, *Target Levels*, *Frequencies*, and *Responsibilities* for measuring each of the five characteristics of a quality pavement.

- Criteria represents **What** should be measured.
- Tools identify **How** best to collect and analyze the data associated with each of the specific measurement Criteria, which MassPQP ultimately selects.
- Target Levels represent **Where** the performance level is expected to be for each of the measurement Criteria selected.

They are the "optimal" measurement values, which the MassPQP believes can and should be achieved by a Quality Pavement system. Until sufficient measurement data from Massachusetts pavements has been collected and statistically evaluated, appropriate Pavement Quality Target Levels cannot be established by the MassPQP.

- Frequency identifies **When** each of the Criteria should be measured. Depending on the Criterion being measured, there may be multiple intervals at which measurement should be made.
- Responsibility indicates **Who** should measure the specific Criteria. Assignment of responsibility will be dependent upon when the measurement is required and will be developed for each of the measurement Criteria selected.

Figure 14.4 is a worksheet that was developed during the Pavement Quality Measurement Workshop. The criteria, method and target level for each quality pavement characteristic are indentified.

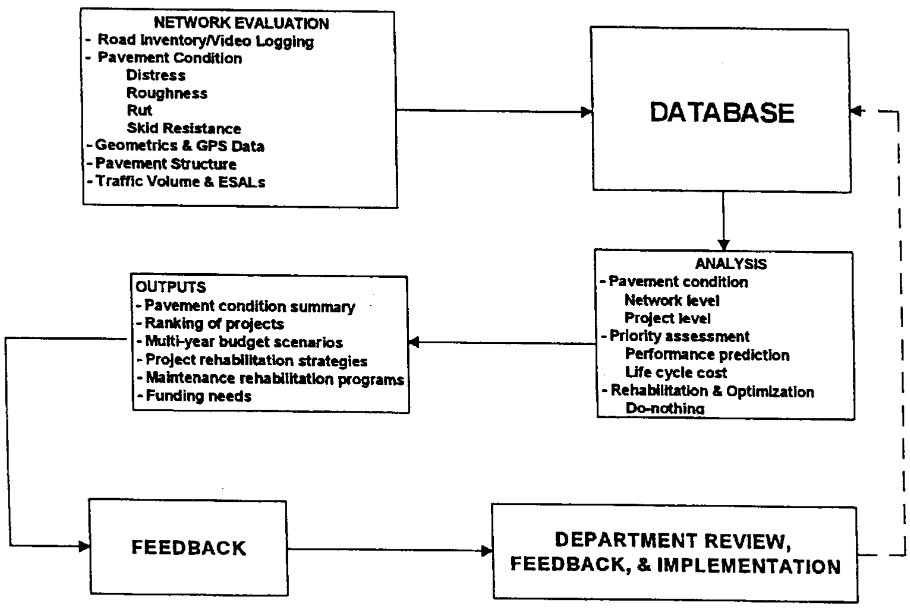
Figure 14.4 Pavement Quality Measurement Workshop spreadsheets (2)

Quality Pavement Characteristic	Criteria to Measure Pavement Quality (What)	Tools, Techniques, Technology to Measure Pavement Quality (How)	Interim Target Level	When Measured	Who Measures
1. Smoothest practical ride	• IRI (initial) • Subjective ride index • PSR	• ARAN (above 40 MPH) or Profilometer • Subjective rater (driver survey) • Panel	• < 70 for new pvmt. • Good • 4.5	• Project QC/QA completion • During service life • New	• QC Contractor QA Owner • Owner • PMS
2. Safest pavement surface	• Skid resistance • Accident rate • Drain • Rutting • Aggregate hardness • Mix design • Wet/dry accident ratio	• Skid tester • Accident/1,000,000 vehicle miles • Visual/straight edge • Visual/straight edge/ARAN • L.A. abrasion • Marshall/SHRP • Accident records	• Based on design speed flagged action • TBD • Action item - no standing water • 0 < .5" • < 30 • To be determined • > the avg. W/D	• When completed as req. every 3 years • Annually • During and after rain • Every 3 years • Prior to use • Prior to use • Annually	• Owner • Owner • Owner • PMS • LAB • LAB • Owner
3. Lowest possible maintenance	• Adherence to specifications • Utilize life-cycle cost • Lane mile cost • Conformance to spec	• Marshall - inspection and testing • Pavement mgmt. (data collecting) • Maintenance records • Testing	• Start using Marshall Increase freq. • Lowest LCC • Lowest cost • Conformance to spec	• During mix production/activity • Prior to design • Prior to design • During constr.	• Owner • Owner • Owner • Cert. tech.
4. Lowest Life-Cycle cost	• Initial, maintenance and user costs (annualize) • Protect selection manner • Construction maintenance user cost	• Owner cost and repair records • Pavement management plan • Price est., maintenance rehab. cost, delay cost	• Savings and 100% of projects have lowest • Life-cycle cost - priority index • 100% of project design, monitored during construction	• On-going • TBD • During design and construction	• Owner • TBD • PMS, owner, contractor
5. Most environmentally friendly	• Air quality • Responsible recycling • Noise • Solvents and additives • Good construction practices	• Traffic control TMP • Mix design (in place) • Grooving, saw cuts - mix design • TBD • Supervision	• EPA standard • Base 30% , binder 25%, top 10% • Decibels • TBD • No complaints	• During and after operations • Prior and during construction • After constr. • Lay down • TBD	• Owner • Owner/Contr. • Owner • Owner/Contr. • TBD

pavements is a function of many discrete activities performed by many different people and organizations. Individually, these activities form a series of Pavement Processes. Collectively, these activities form a Pavement Quality Process. The MassPQP implementation required a clear identification and understanding of existing pavement processes. Accordingly, the workshops focus much of their effort on identifying the overall “Pavement Quality Process” and corresponding individual “Pavement Processes”.

Flow Chart Development During the workshops, each work team prepared a flowchart, or process diagram, of its respective Pavement Process based upon the team members perception and understanding of the current process. These process diagrams are useful tools to help identify bottlenecks, obsolete activities, or missing activities that affect the individual Pavement Process and determine the effectiveness of the Pavement Process in delivering quality pavements. Figure 14.5 is an example of a flow chart for the pavement management process as defined by the pavement management work group.

Figure 14.5 Example Process Diagram (2)



Structured Problem Solving For pavement quality improvements to occur, the PQP must first have an understanding of the issues that most significantly restrain the overall Pavement Quality Process from functioning at its established levels of performance. In implementing the MassPQP, the Process Issues are identified, classified, and prioritized. After the process Issues are identified by the work teams, they are classified as either *Problems* or *Barriers*. Problems are defined as those process issues that are under the direct control or strong influence of the PQP. Barriers are defined as those process issues that are under the direct control or strong influence of the PQP. Problems and Barriers are further classified as short-term or long-term. Short-term Process Issues are defined as having a high probability of being corrected within 12 months or less. Long-term Process Issues are those issues estimated to require between one and five years to correct. Understanding and classifying Process Issues provides a clearer direction for determining where to properly focus CQI efforts.

After charting the current seven Pavement Processes and identifying the Top Pavment Quality Porcess Issues, the work teams go through a structured problem solving model to identify Proposed Process Improvements and to develop corresponding Action Plans to address the top Process Issues. Figure 14.6 shows examples of pavement quality issues and proposed pavement quality process improvements. It should be noted that this does not represent a complete or fail-proof list of statistically based process improvements. The Action Plans comprise the main structure of the Strategic Plan. Figure 14.7 shows an example of an Action Plan.

Figure 14.6 Pavement Quality Process Issues and Improvements (2)

Top Pavement Quality Process Issues

Team	Issue
#5 Pavement Construction Process	1. Poor paving practice and procedure. 2. Detrimental effects from short paving hours. 3. Poor interaction between field personnel and designers.
#6 Pavement Maintenance Process	1. Differential settlement of pavement due to utility cuts. 2. Water infiltration of open cracks and joints. 3. Pavement deformation; shoving and rutting at intersections. 4. Pavement reconstruction/resurfacing projects do not adequately improve drainage features. 5. Maintenance "problems" are not recognized during project construction.
#7 Pavement Management Process	1. The pavement management network process has not been implemented. 2. Lack of project level selection and implementation. 3. The PMS database is incomplete.

Proposed Pavement Quality Process Improvements

Team	Issue
#6 Pavement Maintenance Process	1. Implement design policy that addresses maintenance issues. 2. Implement policy that allows Maintenance personnel some control over construction projects. 3. Develop crack sealing policy. 4. Use concrete at intersections that have unstable mixes. 5. Improve bituminous-concrete mix design to be more stable under heavy loads.
#7 Pavement Management Process	1. Expand and improve PMS database. 2. Get feedback from all other processes. 3. Incorporate all branches of pavement design. 4. Train District personnel in PMS Process.

Figure 14.7 Sample Action Plan (2)

Issue: Differential settlement of pavement due to utility cuts														
Action Items	**Sept. 1995**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept. 1996**	**Beyond**
Improve permit language														
1. Meet with this Comm. and all State Permit Engineers														
2. Draft new permit language														
3. Meet with utility companies and associations for comments														
4. Review comments with utility engineers														
5. Draft final language														
6. Implement new policy														

MAINTAINING THE MASSPQP INITIATIVE

Work Team Action Plan Implementation Process Since the backbone of the Strategic Plan is the Work Team Action Plans, focusing on their implementation is of utmost importance. In the MassPQP, the seven work teams will meet regularly and initiate activities necessary to implement each of their Action Plans. Action Plans may need to be revised to reflect anew information or changed circumstances once implementation begins.

A Quality Measurement System Study will be performed to develop recommendations on final criteria, tools, target levels, frequencies and responsbility of measurement. The study will also identify where data will be collected, and how it will be evaluated. The study will also recommend whether to develop the Pavement Quality Measurement System as part of an existing management system or as a new system.

Progress Monitoring The work team leaders will be responsible for monitoring and reporting progress on individual action plans. The MassPQP co-chairs will be responsible for monitoring the Quality Measurement System Study.

14.4 Summary

Improving and maintaining pavement quality in a cost-effective manner is the primary objective of a PMS. The larger picture, in terms of quality management, is to also to improve quality in other aspects of a state highway agency that affect pavements, such as maintenance and construction. This module attempts to illustrate how a PMS fits into a quality management program. As was shown in Figure 14.1, PMS is necessary, indeed it forms the core of the entire program when the goal is a quality pavement.

REFERENCES

1. Lam, K.D., Watson, F. D. and Schmidt, S.R., Total Quality, a Textbook of Strategic Quality, Leadership and Planning, Air Academy Press, Colorado Springs, CO, 1991.

2. Massachusetts Pavement Quality Partnership, “Strategic Plan, 1995-96”, FMI Corporation, Raleigh, NC, 1996.

3. Personal interview with Greg Doyle and Matt Turo, June 1997.

WORKSHOP 1: SETTING UP A PMS

OBJECTIVE

This workshop has been designed for you to design and develop a PMS. You will need to define your pavement network and consider the addition of many databases and location referencing systems and other information covered in more specific inventory and history data elements. Also consider the use of Modules 1 to 4.

Background

You are a pavement engineer and you have been assigned the responsibility of developing a pavement management system for a small, rural state called Ecotopia. You work for Ecotopia's Department of Transportation. Ecotopia maintains approximately 8,000 km of paved highways, of which 40% belongs to the National Highway System. The remainder of the network consists of a variety of highways ranging from rural two-lane highways to four-lane urban freeways.

Geographically and climatically, Ecotopia is a homogeneous state with the exception of a mountain range in the western region. The mountains extend the length of the state, and reach heights of 2,500 m (7,500 feet). There are distinctly different climatic variables here such as greater precipitation levels, as well as more extreme temperature ranges.

The annual construction budget is approximately $300 million, but this also includes all work related to drainage, bridges, markings and other elements related to the pavement infrastructure as well as some capacity enhancements. It is estimated that $200 million is available on pavement-related projects such as overlays, seals and reconstruction. The operating budget for the pavement management system division is approximately $350,000, which includes your salary. In addition you have been provided a budget of $300,000 to develop and implement the pavement management system.

Much of the NHS system is more than 20 years old and deteriorating. The recession in the early 1990's had a significant impact on Ecotopia and construction and maintenance budgets were reduced by 10%. In addition, there have been organizational changes within EDOT, and considerable downsizing through attrition and retirements.

Systems that are already in place and may possibly be used in the PMS are:

1. Planning type data base which includes network information such as (though there may be some resistance to providing access to these files):
    - Route Log System (using mile post LRS)
    - Highway inventory file (lane and shoulder information)
    - Traffic volume file

- § Volume / Capacity level of service information
- § Planned construction program file

2. EDOT is looking at implementing a GIS but full implementation looks like it will be 5 to 10 years off.

   - § Construction type data base
     - Construction Management System
       - Current construction projects
       - Unit construction costs

   - § Maintenance Data Base
     - Maintenance activities by activity code including (By route and general location)
       - Labor, Equipment, and Materials
       - Total Cost

Because of the rural nature of this state the construction as-built records are only available in paper file format. However, most DOT Districts have kept general track of what was built when and where on a series of strip maps which showed the contract number, date constructed, and general work such as 2 inch overlay, added lanes, etc.

Time Frame

A 90-minute period has been scheduled for this workshop. Your group will meet for an hour and the remaining time will be used for presentations.

Instructions

Consider some of the following issues. Note that this is not an exhaustive list, so there may be other questions and issues that you should consider in your discussions. As you address them, use the issues and questions provided as guidelines. Each group will identify additional factors that contribute to the solutions they feel are most appropriate for the given set of circumstances.

- What does EDOT want to address in a PMS?
- What kind of questions does EDOT want to answer? (network vs. project level)
- Identify you goals and objectives for the PMS (i.e. Mission Statement)
- What components of a PMS do you envision will be required?
- What type of products or outputs do you want to obtain?
- What are some of the constraints that you will encounter?

Specifically in this workshop, you will also develop a detailed description of the database structure, a method for location referencing, and the types of inventory and historical data that will be needed. Expand on all of the data elements that will be included in your proposed PMS. The following are some of the factors and issues to be considered. Again, as you address them, use them as guidelines. Each group will identify additional factors that contribute to the solutions they feel are most appropriate for the given set of circumstances.

- What is the pavement network? (i.e. Total System, or National Highway System)
- What kind of database will be used?
- What location referencing system should be used? Is GPS needed? GIS?
- What types of inventory information should be included? Why? GPR?
- What kind of historical information is needed? Why?
- What kind of quality control is needed?
- What data elements should be included in the historical database? Why?

Please show the reasons for all selected file systems and data elements that will be included in the PMS.

IMPORTANT: Before you begin, select a spokesperson in your group to record and present your group’s findings for this and future workshops.

Deliverable

Your deliverable will be a one-page summary of issues considered by the group as a whole. This will be presented at the conclusion of this workshop in a 5-minute presentation. List all assumptions you made and constraints you considered pertinent.

WORKSHOP 2: DATA COLLECTION

Objectives

In Workshop 1, your group developed a general overview of the PMS that will be used for the workshops in this course. Details on databases and referencing systems, as well as inventory and history data elements were covered. Workshop 2 will now consider all of the data elements that should be included in the PMS database following the modules on pavement condition surveys, condition indices and traffic data.

Timeframe

A two-hour period has been scheduled for this workshop. Your group will meet for 1 to 1 ½ hours and the remaining time will be used for presentations.

Instructions

Specifically in Workshop 2, you will develop a detailed description of the general makeup of the PMS database and the data elements that will be collected and maintained in their database. Expand on all of the data elements that will be included in the PMS including those elements that were developed in more general terms in Workshops 1.

The following are some of the factors and issues to be considered. Again, as you address them, use them as guidelines. Each group will identify additional factors that contribute to the solutions they feel are most appropriate for the given set of circumstances.

- What database should be used?
- What location referencing system should be used?
- What data elements should be included in the <u>historical</u> database?
- What data elements should be included in the <u>monitored</u> database?
- What condition index will be used? (ride, cracking, etc developed by the group)
- What survey procedure will be used?
- Will other data elements be collected? (drainage, structure etc.)
- Which data elements defined above are needed to support the goals defined in the first workshop.
- What level of traffic information will you include in the database?

Please show the reasons for all selected database and data collected, and data and an estimated cost that when totaled which should not exceed the PMS operating budget. Costs should also include software costs. If costs are a constraint, consider plans to obtain more funds (but support with costs and benefits).

Here are some estimates for costs for various pavement condition survey items: If you have better estimates from local experience use those costs.

§ Ride	$10/ kilometer
§ Friction	$15/ kilometer
§ Condition	

	Walking	$125/ kilometer
	Shoulder drive	$10/ kilometer
	Automated	$25 to $50/ kilometer
§	Structure (FWD)	$50 to $100/ kilometer

Other general inventory elements

§ Traffic

AADT & % trucks	$25 to $50/kilometer
ESAL Flow Map	$50 to $100/kilometer

§ Pavement Depths (GPR) $25 to $50/kilometer

Deliverable

Your deliverable will be a one-page summary of issues considered by the group as a whole. This will be presented at the conclusion of this workshop. List all assumptions you made and constraints you considered pertinent.

WORKSHOP 3: PERFORMANCE MODELS & IMPLEMENTATION

Objectives

This workshop is designed to build on the pavement management system design from earlier workshops. During this workshop, your group will outline a modeling approach that will be used for the development of pavement deterioration models and investigate the use of prioritization or optimization for program development. In addition, your group will design a feedback system and outline plans for addressing implementation issues that may be expected within the organization.

Timeframe

A two-hour period has been scheduled for this workshop. Your group will meet for 1 to 1 ½ hours and the remaining time will be used for presentations.

Instructions

Based on the decisions made during the previous workshops, outline an approach that could be followed for developing pavement performance models. Think about the types of data that will be needed for the models and the types of data you specified for data collection activities.

- Are there additional data elements that will be needed to implement the models you design?
- How will you maintain the data over time so that the models can be updated regularly?
- Outline the approach that you will use for the development of multi-year plans.
- Will you use optimization or prioritization? Why?
- What will you need to implement this approach?
- Who should be involved in the process?
- How will you explain the system recommendations to management?
- Do you envision the need for an iterative process to develop the multi-year program or will the system recommendations suffice?

Pavement management systems can be used to provide feedback to others within the organization.

- How does your group propose to use the pavement management information within your organization?
- Who will benefit from this information?
- How frequently will they need the information?
- Is the network-level information satisfactory for the feedback you propose?

Identify and address any implementation issues you think you may need to address within your organization.

- How will you overcome these issues?
- Are there any issues that you think may be insurmountable?
- How will you maintain support from top management?
- What level of resources will you need in the future to maintain the system?

Refer back to list of constraints from the first workshop.

As you address these issues, use the questions provided as guidelines. Each group will identify additional factors that contribute to the solutions they feel are most appropriate for the given set of circumstances.

Deliverable

Your deliverable will be a one-page summary of issues considered by the group as a whole. This will be presented at the conclusion of this workshop. List all assumptions you made and constraints you considered pertinent.

APPENDIX 5A

DISTRESS EVALUATION REFERENCE CHARTS

NEW MEXICO HIGHWAY AND TRANSPORTATION DEPARTMENT

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

FLEXIBLE PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
RAVELING AND WEATHERING	Low: (1)	Aggregate or binder started to wear away on pavement surface. Some dislodged aggregate can be found on the shoulder.	Low: (1)	1% to 30% of test section.
Wearing away of pavement surface, due to dislodged aggregate particles and loss of asphalt binder. Normally, the extent will be throughout the test section.	Med: (2)	Aggregate or binder has worn away. Surface texture is rough and pitted.	Med: (2)	31% to 60% of test section.
	High: (3)	Aggregate and/or binder has worn away, and surface texture is severely rough and pitted.	High: (3)	61% of test section, or more.
BLEEDING	Low: (1)	Film is evident, but aggregate can still be seen. Spotty	Low: (1)	1% of 30% of test section.
Film of bituminous material on pavement surface.	Med: (2)	Film is clearly seen, covers most of the aggregate, and is a little sticky.	Med: (2)	31% to 60% of test section.
	High: (3)	Film is predominant, very sticky, and material is thick enough to shove.	High: (3)	61% of test section, or more.
POLISHED AGGREGATE	Low: (1)	Some of the aggregate is smooth in spots.	Low: (1)	1% to 30% of test section.
Smoothing of aggregate particles due to wear. Normally, the extent will be throughout the test section.	Med: (2)	Aggregate is smooth; however, it still shows stability.	Med: (2)	31% to 60% of test section
	High: (3)	Aggregate is shiny, glazed, and looks slippery.	High: (3)	61% of test section, or more.
CORRUGATION	Low: (1)	Causes some vibration in vehicle, with little or no discomfort.	Low: (1)	0 to 5 feet in test section.
Displacement of pavement typified by ripples across the pavement surface.	Med: (2)	Causes steady vibration in vehicle, and creates moderate discomfort.	Med: (2)	5 to 10 feet in test section.
	High: (3)	Causes excessive vibration in vehicle, creates high level of discomfort, and causes speed reduction.	High: (3)	Over 10 feet in test section.
RUTTING AND SHOVING	Low: (1)	1/4- to 1/2-inch in depth.	Low: (1)	1% to 30% of test section.
Longitudinal surface depressions in wheel path. Check with a 4-foot rut bar.	Med: (2)	1/2- to 1-inch in depth.	Med: (2)	31% to 60% of test section.
	High: (3)	More than 1-inch in depth.	High: (3)	61% of test section, or more.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

FLEXIBLE PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
DEPRESSIONS	Low: (1)	Some vehicle bounce at posted speed; no discomfort.	Low: (1)	One per test section.
Surface areas which have lower elevations than surrounding areas.	Med: (2)	Significant vehicle bounce at posted speed; moderate discomfort.	Med: (2)	Two per test section.
	High: (3)	Excessive vehicle bounce at posted speed; requires speed reduction.	High: (3)	Three or more per test section.
SETTLEMENT AT STRUCTURE	Rate same as depressions, but occurs at a structure (box culvert, pipe, utility cut, etc.).			
SWELLS	Low: (1)	Some vehicle bounce at posted speed, no discomfort. About 1/2-inch to 1-inch high.	Low: (1)	One per test section.
Upward bulge in pavement surface. May occur as a long, gradual wave or sharply over a small area.	Med: (2)	Significant vehicle bounce at posted speed, moderate discomfort. About 1-inch to 2-inches high.	Med: (2)	Two per test section.
	High: (3)	Excessive vehicle bounce at posted speed, requires speed reduction. Over 2-inches high.	High: (3)	Three or more per test section.
POT HOLES	Low: (1)	Less than two square feet <u>and</u> less than 1-inch deep.	Low: (1)	One per test section.
A bowl-shaped hole of various sizes in the pavement surface.	Med: (2)	a. Less than one square foot <u>and</u> more than 1-inch deep.	Med: (2)	Two per test section.
		b. One to two square feet <u>and</u> 1-inch to 2-inches deep.		
		c. Greater than two square feet <u>and</u> less than 1-inch deep.		
	High: (3)	a. One to two square feet <u>and</u> more than 2-inches deep.	High: (3)	Three or more per test section.
		b. Over two square feet <u>and</u> more than 1-inch deep.		

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

FLEXIBLE PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
CRACKS	Low: (1)	Sealed or non-sealed with a mean width of less than 1/4 inch. May have very minor spalls.	Low: (1)	1% to 30% of test section.
Longitudinal: a. Wheel Track b. Mid Lane c. Center Line (Lane/Shoulder Line)	Med: (2)	a. Sealed or non-sealed, and moderately spalled. Any width. b. Sealed, but sealant separated, allowing water to penetrate.	Med: (2)	31% to 60% of test section.
Transverse: a. Partial Width b. Full Width		c. Non-sealed cracks that are not spalled, but are over 1/4-inch wide. d. Low-severity alligator cracks exist near crack, or at the corners of intersecting cracks.		
	High: (3)	a. Severely spalled, any width. b. Medium- to high-severity alligator cracking exists near the crack, or at the corners of intersecting cracks. c. Causes a severe bump to vehicle.	High: (3)	61% of test section, or more.
ALLIGATOR CRACKS	Low: (1)	Hairline – disconnected. 1/8 inch wide, or less. No spalls.	Low: (1)	1% to 30% of test section.
Pattern or interconnected cracks resembling chicken-wire or alligator skin.	Med: (2)	Fully developed cracks greater than 3/8-inch wide. Lightly spalled.	Med: (2)	31% to 60% of test section.
a. Inside Wheel Track. b. Outside Wheel Track. c. Lane Wide (Non-Wheel Track)	High: (3)	Severely spalled. Cells rock. May pump.	High: (3)	61% of test section, or more.
BLOCK CRACKING	Low: (1)	1/4-inch wide, or less. No spalls. May be sealed.	Low: (1)	1% to 30% of test section.
Pattern of cracks, which divide the asphalt surface into roughly	Med: (2)	Greater than 1/4-inch wide. Minor spalls.	Med: (2)	31% to 60% of test section.
rectangular sections ranging in size from 1 to 100 square feet.	High: (3)	Severely spalled cracks.	High: (3)	61% of test section, or more.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

FLEXIBLE PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
SLIPPAGE CRACKS	Low: (1)	1/4-inch wide, or less. No spalls.	Low: (1)	1% to 30% of test section.
Crescent or half-moon shaped cracks, generally having two ends which point into the direction of vehicle travel.	Med: (2)	Greater than 1/4-inch wide. Some spalls.	Med: (2)	31% to 60% of test section.
	High: (3)	Severely spalled.	High: (3)	61% of test section, or more.
EDGE CRACKS	Low: (1)	1/4-inch wide, or less. No spalls.	Low: (1)	1% to 30% of test section.
Cracks which occur on the edge of the pavement.	Med: (2)	Greater than 1/4-inch wide. Some spalls.	Med: (2)	31% to 60% of test section.
	High: (3)	Severely spalled.	High: (3)	61% of test section, or more.
RANDOM CRACKS	Low: (1)	1/4-inch wide, orless. No spalls.	Low: (1)	1% to 30% of test section.
Cracks which do not fit the descriptions for any of the above types of cracking patterns.	Med: (2)	Greater than 1/4" wide. Some spalls.	Med: (2)	31% to 60% of test section.
	High: (3)	Severely spalled.	High: (3)	61% of test section, or more.
				Hot Mix Patch
PATCHING	Low: (1)	Patch is present, and is in good condition.	Low: (1)	One patch in test section.
			Med: (2)	Two patches in test section.
An area where the original pavement has been removed and replaced with similar or different material.	Med: (2)	Somewhat deteriorated. Low to medium of any type of distress on patch.	High: (3)	Three or more patches in test section.
				Skin Patch
a. Hot Mix b. Skin c. Other	High: (3)	Patch is deteriorated to point of soon or immediately needing replacement.	Low: (1)	Covers less than 30% of test section.
			Med: (2)	Covers 31% to 50% of test section.
			High: (3)	Covers over 50% of test section.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

RIGID PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
BLOW-UP	Low: (1)	Buckling or shattering has occurred; some vehicle bounce; no discomfort.	Low: (1)	One per test section.
Blow-ups occur in hot weather at transverse joints or cracks which will not permit expansion of slabs. Usually caused by incompressibles in joint space. Localized upward movement of slab edges (buckling) or shattering occurs near the joint.	Med: (2)	Buckling or shattering has occurred; significant bounce; some discomfort. Temporary patching may exist.	Med: (2)	Two per test section.
	High: (3)	Severe buckling or shattering; excessive vehicle bounce; substantial discomfort and/or vehicle damage, requiring speed reduction.	High: (3)	Three or more per test section.
CORNER BREAK	Low: (1)	Crack is tight (hairline). Well-sealed cracks considered tight. No faulting or break-up.	Low: (1)	1 to 3 per test section.
Crack intersects joints at a distance less than 6 feet on either side, measured from corner. Crack extends vertically through entire slab thickness.	Med: (2)	Crack is working and spalled at low or medium severity. No break-up or corner. Faulting of crack or joint less than 1/2-inch. Temporary patching may exist.	Med: (2)	4 to 6 per test section.
	High: (3)	Crack is spalled at high severity, or the corner has broken into 2 or more pieces, or faulting more than 1/2 inch.	High: (3)	Seven or more per test section.
DEPRESSION	Low: (1)	Some vehicle bounce; little or no discomfort.	Low: (1)	One per test section.
Areas having lower elevations than that of the surrounding pavement. Significant slab cracking is usually found in these areas, due to uneven settlement.	Med: (2)	Significant vehicle bounce; moderate discomfort.	Med: (2)	Two per test section.
	High: (3)	Excessive vehicle bounce; substantial discomfort. Requires speed reduction.	High: (3)	Three or more per test section.
FAULTING OF TRANSVERSE JOINTS AND CRACKS	Low: (1)	Faulted joints or cracks average 1/16 inch or less.	Low: (1)	1% to 30% of test section.
Elevation difference across a transverse joint or crack.	Med: (2)	Faulted joints or cracks average more than 1/16 inch, but less than 1/5 inch.	Med: (2)	31% to 60% of test section.
	High: (3)	Faulted joints or cracks average 1/5 inch or more.	High: (3)	61% of test section, or more.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

RIGID PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
JOINT SEAL DAMAGE OF TRANSVERSE JOINTS	Low: (1)	Sealer is in generally good condition, with only minor damage. Little water, and no incompressibles can infiltrate the joint.	Low: (1)	1% to 30% of test section.
Any condition which allows incompressibles or water to infiltrate the joint from the surface.	Med: (2)	Sealer is in generally fair condition, with one or more types of damage occurring to a moderate degree. Water can infiltrate fairly easily; some incompressibles can infiltrate also.	Med: (2)	31% to 60% of test section.
Types of joint seal damage: ----- joint sealant stripping ----- joint sealant extrusion ----- weed growth ----- hardening of filler ----- loss of bond to slab edges ----- joint sealant absence	High: (3)	Sealer is in generally poor condition, with one or more types of damage occurring to a severe degree. Water and incompressibles infiltrate freely.	High: (3)	61% of test section, or more.
LANE/SHOULDER DROP-OFF OR HEAVE	Low: (1)	Elevation difference: 1/4 to 1/2 inch.	Low: (1)	1% to 30% of test section.
Difference in elevation between the traffic lane and shoulder.	Med: (2)	Elevation difference: 1/2 to one inch.	Med: (2)	31% to 60% of test section.
	High: (3)	Elevation difference: one inch or more.	High: (3)	61% of test section, or more.
LANE/SHOULDER JOINT SEPARATION	Low: (1)	Separation: 1/8 inch or less.	Low: (1)	1% to 30% of test section.
Opening of joint between the traffic lane and the shoulder, generally due to movement of the shoulder.	Med: (2)	Separation: 1/8 inch to 4/10 inch.	Med: (2)	31% to 60% of test section.
	High: (3)	Separation: more than 4/10 inch.	High: (3)	61% of test section, or more.
LONGITUDINAL CRACKS	Low: (1)	Hairline crack with no spalling or faulting.	Low: (1)	1 to 3 per test section.
Cracks run generally parallel to the pavement centerline.	Med: (2)	Working crack with low to moderately severe spalling and/or faulting less than 1/2 inch.	Med: (2)	4 to 6 per test section.
	High: (3)	Crack greater than 1 inch wide; high severity spalling; faulted 1/2 inch or more.	High: (3)	Seven or more per test section.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

RIGID PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
LONGITUDINAL JOINT FAULTING	Low: (1)	Some faulting, but less than 1/4 inch.	Low: (1)	1% to 30% of test section.
Elevation difference across a longitudinal joint between traffic lanes.	Med: (2)	Faulting of 1/4 inch to 1/2 inch.	Med: (2)	31% to 60% of test section.
	High: (3)	Faulting of 1/2 inch or more.	High: (3)	61% of test section, or more.
PATCH DETERIORATION	Low: (1)	Patch functioning well with little or no deterioration. Low severity spalling of patch edges may exist. Faulting across the slab-patch joint less than 1/4 inch. Rated low even if in excellent condition.	Low: (1)	One per test section
Area where part of original pavement has been replaced or covered with similar or different material.	Med: (2)	Patch has low severity cracking, and/or some spalling of medium severity around the edges. Temporary patches have been placed because of permanent patch deterioration.	Med: (2)	Two per test section.
	High: (3)	Patch has deteriorated to a condition which requires replacement, due to spalling, rutting or cracking within the patch.	High: (3)	Three or more per test section.
POPOUTS		No degrees of severity are defined. However, popouts must be extensive before they are counted as a distress; average popout density must exceed approximately one per square yard over the entire slab.	Low: (1)	1% to 30% of test section.
Small pieces of concrete that break loose from the pavement surface. Popouts. usually range from about 1 inch to 4 inches in diameter, and from 1/2 inch to 2 inches deep.			Med: (2)	31% to 60% of test section.
			High: (3)	61% of test section, or more.
PUMPING AND WATER BLEEDING	Low: (1)	Water is forced out of a joint/crack when trucks pass over the joint/crack. Water is forced out of the lane/shoulder joint when trucks pass along the joint. No fines can be seen on either the traffic lanes or shoulder.	Low: (1)	1% to 30% of test section.
Ejection of material by water through joints or cracks, caused by deflection of the slab under moving loads. Accumulation of silt, sand, clay or gravel on the surface is evidence of pumping.	Med: (2)	A small amount of pumped material is near some of the joints/cracks on the traffic lane or shoulder.	Med: (2)	31% to 60% of test section.
	High: (3)	A significant amount of pumped material is on the surface of of either the traffic lane or shoulder along the joints/cracks.	High: (3)	61% of test section, or more.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

RIGID PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
SCALING, MAP CRACKING, AND CRAZING Map cracking or crazing refers to a network of shallow, fine, or hairline cracks which extend only through the upper surface of the concrete. This condition may lead to scaling of the surface. Scaling is the breakdown of the slab surface to a depth of approximately 1/4 inch.	Low: (1)	Crazing or map cracking exists over most of the slab area; the surface is in good condition, with no scaling.	Low: (1)	1% to 30% of test section.
	Med: (2)	Less than 10% of any slab exhibits scaling.	Med: (2)	31% to 60% of test section.
	High: (3)	More than 10% of any slab exhibit scaling.	High: (3)	61% of test section, or more.
SPALLING OF TRANSVERSE AND LONGITUDINAL JOINTS AND CRACKS Cracking, breaking or chipping of slab edges within 2 feet of the joint. Spall does not extend vertically through the slab, but angles through the slab to the joint/crack.	Low: (1)	Spall less than 2 feet long; if spall is broken and fragmented, must not extend more than 3 inches from joint/crack. Spallls more than 2 feet long with spall held tightly in place; if cracked, only 2 or 3 pieces. Joint/crack is lightly frayed: fray extends less than 3 inches from edge of joint/crack.	Low: (1)	1% to 30% of test section. Normally, the extent will be throughout the test section.
	Med: (2)	One of the following conditions exists: a. Spall broken into pieces; spall extends more than 3 inches from joint/crack. b. Some or all pieces loose or missing, but do not present a hazard. c. Joint/crack moderately frayed; fray extends more than 3 inches. d. Temporary patching may exist.	Med: (2)	31% to 60% of test section.
	High: (3)	Joint is severely spalled, spall is broken into pieces. Tire damage hazard. Requires speed reduction.	High: (3)	61% of test section, or more.

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

RIGID PAVEMENT DISTRESS EVALUATION REFERENCE CHART

DISTRESS		SEVERITY		EXTENT
SPALLING OF CORNERS Raveling or breakdown of the slab within approximately 2 feet from the corner. A corner spall differs from a corner break in that the spall usually angles downward at about 45 degrees to intersect the joint.	Low: (1)	Spall is not broken into pieces. No spalling of cracks exists. Spall is in place and not loose. Corner spalls with both edges less than 3 inches long will not be counted.	Low: (1)	1 to 3 per test section.
	Med: (2)	One of the following conditions exists: a. Spall is broken into pieces. b. Cracks are spalled. c. Some or all pieces loose or missing, but do not present a hazard. d. Corner spall is patched.	Med: (2)	4 to 6 per test section.
	High: (3)	Spall is broken into pieces. Tire damage hazard. Requires speed reduction.	High: (3)	Seven or more per test section.
SWELLS	Low: (1)	Some vehicle bounce; little or not discomfort.	Low: (1)	One per test section.
Upward bulge in pavement surface. May occur sharply over a small area, or as a longer, gradual wave.	Med: (2)	Significant vehicle bounce, causing moderate discomfort.	Med: (2)	Two per test section.
	High: (3)	Excessive vehicle bounce, causing substantial discomfort. Tire damage hazard. Requires speed reduction.	High: (3)	Three or more per test section.
TRANSVERSE AND DIAGONAL CRACKS	Low: (1)	Hairline crack without spalling or faulting. Well-sealed crack without visible faulting or spalling.	Low: (1)	1 to 3 per test section.
Medium or high severity cracks are working cracks, and are considered major structural distresses. Note: Hairline cracks that are less than 6 feet long are not rated.	Med: (2)	Working crack with low to moderately severe spalling, and/or faulting less than 1/2 inch.	Med: (2)	4 to 6 per test section.
	High: (3)	Crack greater than 1 inch wide; high severity spalling; faulted 1/2 inch or more.	High: (3)	Seven or more per test section.

APPENDIX 5B

PAVEMENT CONDITION DATA COLLECTION PROTOCOLS

The following final draft protocols are currently under development by the Texas Research and Development Foundation as part of their contract with the Federal Highway Administration (Contract No. DTFH61-95-C-00019).

This version of the protocols are dated October 1996.

CRACKING PROTOCOL
FOR ASPHALT SURFACE PAVEMENTS

1. Purpose

1.1 This protocol defines standard procedures for estimating and summarizing cracking on or asphalt pavement surfaces. Standardization will help produce consistent pavement condition estimates for network pavement management. The protocol applies to the National Highway System; application to other highways, streets and roads is left to the user-agency.

2. Scope

2.1 This protocol describes methods for estimating three types of cracking distress on asphalt pavement surfaces. Three cracking distresses will be identified: fatigue, transverse, and miscellaneous.

2.2 Procedures are defined for estimating cracking, but detailed specifications are not included for equipment or instruments making the estimates. Any equipment that can estimate as specified, with the accuracy stipulated herein and which can be adequately calibrated, is considered acceptable for this protocol.

2.3 This protocol does not purport to address all of the safety issues, if any, associated with its use. It is the responsibility of the user of this protocol to establish appropriate safety and health practices and determine applicability of regulatory limitations related to and prior to its use.

2.4 Either automated or manual data collection surveys are acceptable when implementing this protocol.

a) Automated surveys – Use a vehicle traveling at near highway speeds and collect data on the entire length of roadway (100% sample).

b) Manual surveys – View distresses from the side of the roadway and collect data on a minimum 3% sample of the lane surveyed.

3. Cracking Definition and Estimation

3.1 *General Guidelines* – Each agency should designate the lane(s) and direction(s) of travel to be surveyed or rated based on sound engineering principles and management needs within the agency. The following guidelines are recommended to provide long-term uniformity:

a) Survey the outside lane.
b) For undivided highways survey one direction.
c) For divided highways survey the outside lane in both directions.
d) For each survey cycle use the same direction(s) of travel and survey lane(s).

3.2 *Cracking Definition and Types* – A crack is a fissure or discontinuity in the pavement surface, which may not extend through the entire thickness of the pavement. Three types of cracking are defined here: transverse cracking, fatigue cracking, and miscellaneous cracking.

3.2.1 *Transverse Cracking* – A transverse crack is any crack that crosses half the survey lane, excluding saw cuts, that is within 45 degrees of perpendicular to the pavement centerline.

3.2.2 *Fatigue Cracking Definition* – Fatigue cracking consists of cracks in the wheel path not already identified as transverse cracks. It is observed as any or all of the following forms:

a) Longitudinal cracks in the wheel path with few or no intersecting cracks.
b) A series of interconnected, transverse and longitudinal cracks located in the wheel path forming a series of polygons. In the most extreme case, the individual blocks can become loose and develop into “potholes.”

3.2.3 *Miscellaneous Cracking Definition* – Miscellaneous cracking is any crack in the area between wheel paths not identified as transverse. This area is shown in Figure 1. Miscellaneous cracking includes longitudinal cracks, and also interconnected longitudinal and transverse cracks, and also interconnected longitudinal and transverse cracks forming a series of polygons (block cracking).

3.3 Cracking Estimates by Type

3.3.1 *Rating Transverse Cracks* – For transverse cracks, the entire lane is viewed.

a) Identify each transverse crack that crosses half the survey lane.

b) Estimate the mean crack width in millimeters to identify the severity level.

3.3.1.1 Severity Level 1 consists of transverse cracks whose mean crack width is < 6mm.

3.3.1.2 Severity Level 2 consists of transverse cracks whose mean crack width is 6-12mm.

3.3.1.3 Severity Level 3 consists of transverse cracks whose mean crack width is > 12mm.

3.3.2 *Rating Fatigue Cracks* – Fatigue cracking is estimated in the outside wheel path. This area has a transverse width of 0.75 meters (30 inches) centered at the middle of the wheel path as shown in Figure 1.

a) Automated surveys – Classify each meter length of wheel path as one of the following severity levels.

b) Manual surveys – Estimate length(s) of the wheel path with homogeneous fatigue cracking patterns. Then classify each homogeneous length as one of the following severity levels.

3.3.2.1 *Severity Level 1* consists of either of the following two cases:

a) Longitudinal cracks in the wheel path with few or no intersecting cracks, and

b) Intersecting longitudinal and transverse cracking that form large polygons (block cracking > 0.1 m^2) which occur solely in the outside wheel path. If block cracking extends across the mid-area between the wheel paths it will be recorded as miscellaneous cracking and should not be recorded a second time as fatigue cracking.

3.3.2.2 *Severity Level 2* consists of interconnected longitudinal, diagonal, and short transverse cracks in the wheel path whose crack width ranges from hairline to 6mm (0.28 inches). These cracks form a network of polygons, often referred to as alligator or chicken-wire cracks. Some spalling may be observed; however, there will be no loose pieces of asphalt concrete nor will there be any indications of “potholes.” The average size of the pieces formed by the cracks will be less than 0.1 square meters (1 sq. ft.).

3.3.2.3 *Severity Level 3* consists of interconnected longitudinal and transverse cracks that form polygons greater than or equal to 6 mm (0.28 inches) wide.

4. Recording of Data

4.1 *Data Collection Sections* – The exact length of the data collection section is determined by the agency and shall be between 0.10 km and 1.0 km.

a) Automated Surveys – the entire length of the data collection section shall be surveyed (100% sample).

b) Manual Surveys – One 30 m long sample shall be surveyed per data collection section. It should be noted that the 30m sample represents 3% of a 1.0 km section length. To increase sampling percentage, an agency can use a shorter data collection section length.

Data will be recorded as shown in the following sections. The term “sample” will be used as it applied to both automated methods and manual surveys. For automated surveys the sample is collected on the entire length of the data collection section.

4.1.1 *Data Recording for Transverse Cracking* – For each severity level, record the number of transverse cracks in the sample. The data may be recorded in a format similar to Table 1.

Figure 1. Cross Section of Survey Lane Showing Wheel Paths and Defined Survey Area between Wheel Paths

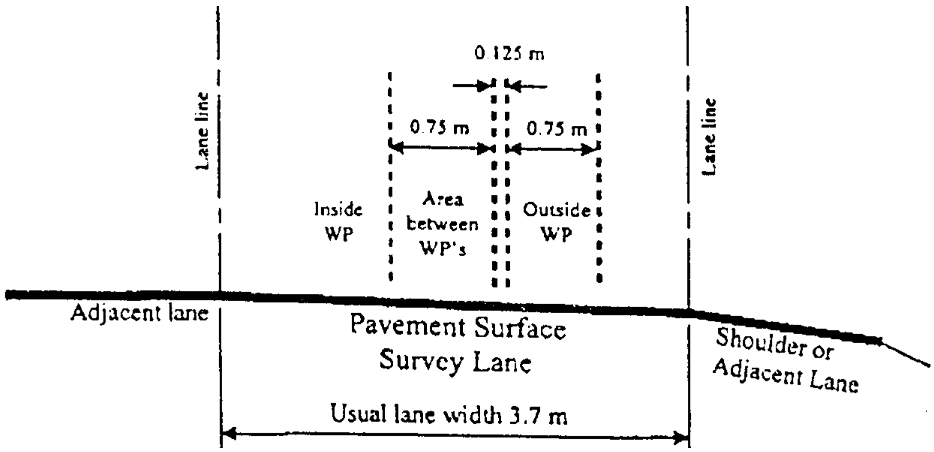


Table 1. Recording of Extent for Transverse Cracking by Severity Level.

Severity Level	**Crack with Range (mm)**	**Extent (# of Cracks)**
Level 1	< 6 mm	
Level 2	6 – 12 mm	
Level 3	>12 mm	

4.1.2 Data Recording for Fatigue Cracking – For each level of severity record the length in the sample attributed to that severity. The data may be recorded in a format similar to Table 2.

Table 2. Recording of Extent for Fatigue Cracking by Severity Level.

Severity Level	**Cracking Pattern and Width**	**Extent * Length of sample affected (m)**
Level 1	Narrow Longitudinal Cracks	
Level 2	Narrow Block Cracks or Wide Longitudinal Cracks	
Level 3	Wide Block Cracks	

* The sum of the lengths recorded for all severity levels of miscellaneous cracking cannot exceed the sample length.

4.2 The minimum data recorded shall contain the following:

a) *Section Identification* – For each data collection section the agency should list all information necessary to locate the section using their current referencing system.
b) Length of the data collection section (m).
c) Length within the sample for each severity level of fatigue cracking (m).
d) Number of transverse cracks within the sample for each severity level (#)
e) Length within the sample for each severity level of miscellaneous cracking (m).
f) The date of collection (month/day/year).
g) Sample location (optional) – the beginning location of the sample.
h) Sample length (m).

5. Quality Assurance

5.1 *Quality Assurance Plan* – Each agency shall develop an adequate quality assurance plan. Quality assurance includes survey personnel certification training, accuracy of equipment, daily quality control procedures, and periodic and on-going control activities. The following guidelines are suggested for developing such a plan.

5.2 *Training* – Certification Training is the training or certification of personnel for proficiency in pavement rating or in operating equipment that must be used as a part of quality assurance. Agencies are individually responsible for training and certifying their survey personnel.

5.3 *Equipment* – The basic output of any used equipment should be checked or calibrated according to the equipment manufacturer's recommendations. The equipment must operate within the manufacturer's specifications. A regular maintenance and testing program should be established for the equipment in accordance with the manufacturer's recommendations.

5.4 *Test Sections* – Test or calibration sections should be located with known cracking types and levels statistics. These sections should be surveyed on a weekly basis. Comparison of these surveys can provide information about the accuracy of surveys and give insight into which raters/operators need additional training. Test sections should be rotated or replaced on a regular basis in order to assure that raters/operators are not repeating known numbers from prior surveys. As an alternate to this procedure, up to 5% of the data may be surveyed again on a daily basis as a quality check.

5.5 *Quality Checks* – Additional quality checks can be made by comparing last year's cracking survey summaries with current surveys. At locations where large changes occur, the pavement manager may consider additional investigation of the data.

CRACKING PROTOCOL ON JOINTED CONCRETE PAVEMENT (JCP)

1. Purpose

1.1 This protocol defines standard procedures for estimating and summarizing cracking of jointed concrete pavement (JCP) surfaces. Standardization will help produce consistent estimates of cracking for network level pavement management. This protocol applies to the National Highway System; application to other highways, streets and roads is left to the user-agency.

2. Scope

2.1 This protocol describes methods for estimating cracking distress and joint related distress for jointed concrete pavement. For transverse joints distresses included are joint spalling and “D” cracking. For slabs distresses included are: shattered slabs, transverse and longitudinal cracking, corner breaks, asphalt patches and surface disintegration.

2.2 Procedures are defined for estimating cracking, but detailed specifications are not included for equipment or instruments to be used to make the estimates. Any equipment which can estimate as specified, with the accuracy stipulated herein and which can be adequately calibrated, is acceptable for this protocol.

2.3 This protocol does not purport to address all of the safety issues, if any, associated with its use. It is the responsibility of the user of this protocol to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2.4 Either automated or manual data collection surveys are acceptable when implementing this protocol.

a) Automated surveys – Use a vehicle traveling at near highway speeds and collect data on the entire length of roadway (100% sample).

b) Manual surveys – View distresses from the side of the roadway and collect data on a minimum 3% sample of the lane surveyed.

3. Cracking Definitions and Estimation

3.1 *General Guidelines* – Each agency should designate the lane(s) and direction(s) of travel to be surveyed based on sound engineering principles and management needs within the agency. The following guidelines are recommended to provide long term uniformity:

a) Survey outside the lane.

b) For undivided highways, survey one direction.

c) For divided highways, survey the outside lane in both directions.

d) For each survey cycle, use the same direction(s) of travel and survey lane(s).

3.2 *General Definitions* – The following definition are given for the purpose of this protocol.

3.2.1. *Slab* – A slab is the concrete surface between the transverse joints.

3.2.2. *Transverse Joint* – A transverse joint is the dividing line between slabs. The joint is usually constructed in a straight line and at right angles to the center line or a slight skew.

3.2.3. *Cracking* – A crack is a fissure or discontinuity in the pavement surface, not necessarily extending through the entire thickness of the pavement.

3.2.4. *Spalling* – Spalling is breaking, chipping, or fretting of the slab surface at a crack or joint.

3.3 Slab Cracking, Distress Definitions – Transverse and longitudinal cracking, shattered slabs, corner breaks, asphalt patches, and surface disintegration are defined as follows:

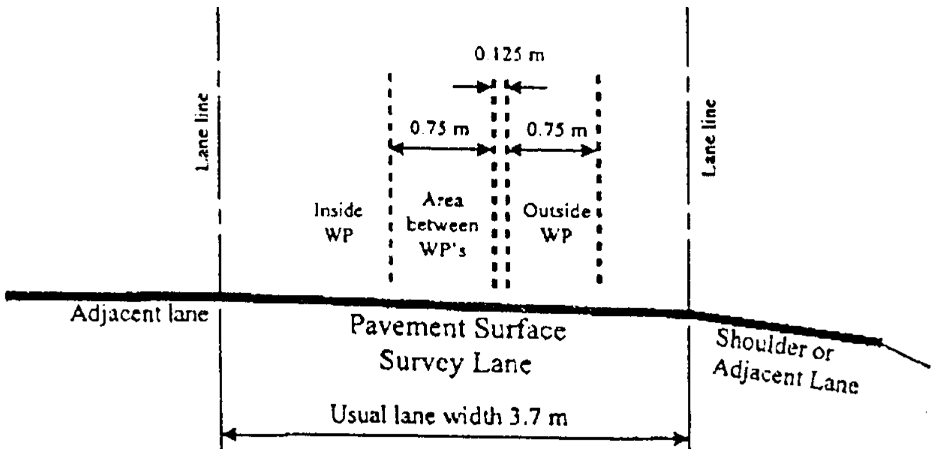
3.3.1. *Shattered Slab* – A slab is shattered when within 6 meters of length measured parallel to center line, the slab is divided into 5 or more sections by cracking. The slab in Figure 1 is shattered.

3.3.2. *Transverse Cracking* – A transverse crack is any crack that crosses half the survey lane within 45 degrees of perpendicular to the pavement centerline.

3.3.3. *Longitudinal Cracking* – A longitudinal crack is any crack longer than two meters that is within 45 degrees of parallel to the pavement centerline.

3.3.4. *Corner Break* – A portion of the slab separated by a crack which intersects the adjacent transverse and longitudinal joint (or slab edge), at approximately a 45 degree angle. The length of the sides range from 0.3 m to half the lane width. See Figure 1 for an example of a corner break.

Figure 1. Example Corner Break and Shattered Slab.



3.3.5. *Asphalt Slab Patch* – An asphalt patch is a temporary repair of a hole in a slab. Asphalt patches can be recognized on white or gray PCC by the darker contrasting color of the asphalt. Spalls filled with asphalt within 0.3 m of a transverse joint are considered spalls, not patches.

3.3.6. *Surface Disintegration* – Surface disintegration is slab deterioration which includes the loss of the thin layer slab surface, and usually results in an unsightly surface texture that is usually rough and noisy.

3.4 *Joint Distress Definitions* - Joint spalling and "D" cracking are defined in the following:

3.4.1. Joint Spalling – Joint spalling is breaking or chipping of slab edges at the joint within 0.3 m of a joint.

3.4.2. "D" Cracking – "D" cracking consists of closely spaced, crescent-shaped, and/or hairline cracking. "D" cracking occurs adjacent to joints (free edges) and slab corners and produces discoloration of the surrounding area.

3.5 *Rating Slab Distress* – Every slab in the survey is surveyed for distress as follows:

3.5.1. Rating Shattered Slab

a) Count the slab sections separated by cracking (Slabs less than 6.0 m in length broken into five or more sections are called shattered.)
b) Do not include corner breaks as slab sections.
c) If slab is shattered no additional ratings of individual cracking distresses are required on the slab.

3.5.1.1 Severity Level 1 (Shattered Slab) – Slab with 5 or more sections in 6 m lengths separated by cracking.

3.5.2. Rating Transverse Cracks and Severity Level

a) Identify longitudinal cracks longer than two meters.
b) Estimate the mean crack width in millimeters for the widest crack found.
c) Identify spalled cracks. A crack is spalled when 10% of its length has spalls wider than 30 mm. (See Figure 2)

3.5.2.1 Severity Level 1 – Any slab with a crack $\leq$ 6 mm in width and not spalled.

3.5.2.2 Severity Level 2 – Any slab with a crack > 6 mm in width and /or spalled crack.

3.5.3. Rating Longitudinal Cracks and Severity Levels.

a) Identify longitudinal cracks longer than two meters.

b) Estimate the mean crack width in millimeters for the widest crack found.

c) Identify cracks with spalling. A crack has spalling when 10% of its length has spalls wider than 30 mm.

3.5.3.1 Severity Level 1 – Slab with any crack ≤ 6 mm in width and not spalled.

3.5.3.2 Severity Level 2 – Slab with any crack > 6 mm in width or spalled cracks.

3.5.4. *Rating Corner Breaks and Severity Levels*

a) Identify corner breaks.

b) Identify if any corner break that has settled with respect to main slab.

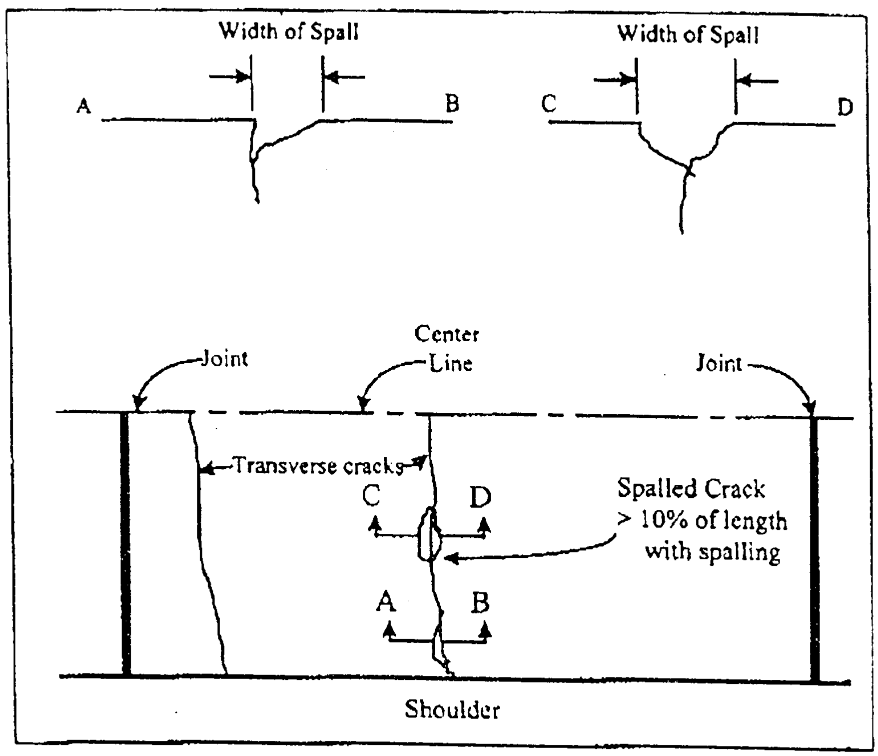
c) Estimate the mean crack width for the widest corner break.

d) Identify cracks with spalling. A crack is spalled when 10% of its length has spalls wider than 30 mm.

3.5.4.1 Severity Level 1 – Slab with corner break crack ≤ 6 mm in width with no spalling.

3.5.4.2 Severity Level 2 – Slab with no corner break crack 6 mm in width, spalled cracks or settlement of corner break.

Figure 2. Illustration of Crack Spalling.



3.5.5. *Rating Surface Disintegration and Severity Levels*

a) Identify area of surface disintegration. The depth of this surface loss is 13 mm.

b) Estimate length (parallel to center line) of slab affected.

3.5.5.1 Severity Level 1 – Slab with > 0.3 m but ≤ 1.0m of length affected.

3.5.5.2 Severity Level 2 – Slab with > 1.0 m of length affected.

3.5.6. *Rating Asphalt Patches and Severity Levels*

a) Identify the asphalt patches in the slab. Soils filled with asphalt within 0.3 m of a transverse joint are considered spalls, not patches.

b) Estimate the area of the patches in sq. m of asphalt patch area.

3.5.6.1 Severity Level – Slab with > 0.3 sq. m but < 1.0 sq. m of asphalt patch area.

3.5.6.2 Severity Level – Slab with > 1.0 sq. m of asphalt patch area.

3.6 Rating Joint Distress – Joint Distress is surveyed in the 0.3 m wide stripe on each side of the joint at each observed slab. See Figure 3 for Illustration of the survey area. Joint spalling and “D” cracking ratings are described in the following.

3.6.1 *Joint Spalling*

a) Identify each joint with spalling or spalls filled with asphalt material.

b) Estimate the width of spalling for the widest 10%. See Figure 3.

3.6.1.1 Severity Level 1 – Joint with spalled width > 30 mm but ≤ 75 mm.

3.6.1.2 Severity Level 2 – Joint with spalled width > 75 mm.

3.6.2 Rating “D” Cracking

a) Identify joints with “D” cracking.

b) Identify severity levels for “D” cracking as shown the following.

3.6.2.1 Severity Level 1 – Joint with tight “D” cracking.

3.6.2.2 Severity Level 2 – Joint with “D” cracks which are discolored and have associated distress such as loose or missing pieces or asphalt patches.

4. Recording of Data

4.1 *Data Collection Sections* – The exact length of the data collection section is determined by the agency and shall be between 0.10 km and 1.0 km.

a) *Automated surveys* – The entire length of the data collection section shall be surveyed (100% sample).

b) *Manual surveys* – Cracking distress will be surveyed on one sample of eight slabs. A typical joint spacing of 6 m (20’) will result in a 48 m sample length. It should be noted that a 48 m sample represents about 5% of a 1.0 km section length. To increase sampling percentage, an agency can use a shorter data collection section length. A full width concrete patch and its additional transverse joints shall be rated with the subsequent or surrounding slab.

Recording of data for slab and joint cracking distress will be discussed in the following sections. The term “sample” will be used as it applies to both automated methods and manual surveys. For automated surveys the sample is the entire length of the data collection section.

4.2 *Data Recording for Slabs* – The slab distress data for the sample may be recorded as follows:

4.2.1 *Data Recording for Shattered Slab* – The extent is recorded as the number of slabs. Only one severity level is defined. The data may be recorded in a format similar to Table 1.

Figure 3. Illustration of Joint Spalling.

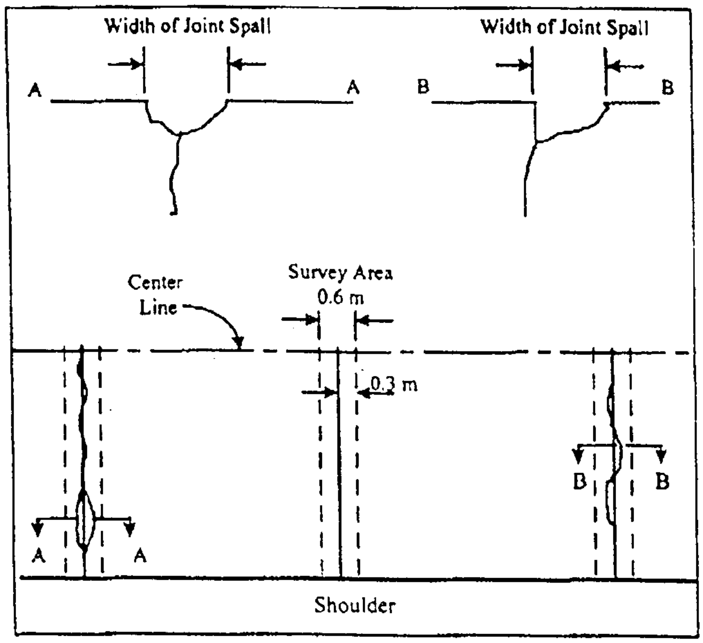


Table 1. Recording of Extent for Shattered Slab by Severity Level.

Severity Level	**Description of Severity**	**Extent (# of Slabs)**
Shattered Slab	Slab divided into five or more sections by cracking within 6 m of slab length	

4.2.2 *Data Recording for Transverse Cracking* – For each level of severity record the number of slabs in the sample attributed to that severity. The data may be recorded in a format similar to Table 2. Record the highest level for either cracking or spalling.

Table 2. Recording of Extent for Transverse Cracking by Severity Level.

Severity Level	**Crack Width and Condition**	**Extent (# of Slabs)**
Level 1	$\leq$ 6 mm and not spalled	
Level 2	> 6 mm or spalled cracks	

4.2.3 *Data Recording for Longitudinal Cracks* – For each level of severity record the number of slabs in the sample attributed to that severity. The data may be recorded in a format similar to Table 3. Record highest level for either cracking or spalling.

Table 3. Recording of Extent for Longitudinal Cracking by Severity Level.

Severity Level	**Crack Width and Condition**	**Extent (# of slabs)**
Level 1	$\leq$ 6 mm and not spalled	
Level 2	> 6 mm or spalled cracks	

4.2.4. *Data Recording for Corner Breaks* – For each level of severity record the number of slabs in the sample attributed to that severity. The data may be recorded in a format similar to Table 4.

Table 4. Recording of Extent for Corner Break by Severity Level.

Severity Level	**Description of Corner Break**	**Extent (# of Slabs)**
Level 1	Crack width $\leq$ 6 mm, not spalled and with no settlement	
Level 2	Crack width > 6 mm, spalled and/or with settlement	

4.2.5. Data Recording for Surface Disintegration – For each level of severity record the number of slabs in the sample attributed to that severity. The data may be recorded in a format similar to Table 5.

Table 5. Recording of Extent for Surface Disintegration by Severity Level.

Severity Level	**Amount of Slab Length Affected (m)**	**Extent (# of Slabs)**
Level 1	0.1 to 1.0	
Level 2	> 1.0	

4.2.6. Data Recording for Asphalt Patches – For each level of severity record the number of slabs in the sample attributed to that severity. The data may be recorded in a format similar to Table 6.

Table 6. Recording of Extent for Asphalt Patches by Severity Level.

Severity Level	**Area of total patches in a slab sq. m**	**Extent (# of Slabs)**
Level 1	> 30 to 75 mm	
Level 2	> 75 mm	

4.3 Data Recording for Joint – The joint following the surveyed slab, in the direction of traffic, will be surveyed. The joint distress data will be recorded as shown as follows:

4.3.1. Data Recording for Joint Spalling – For each level of severity record the number of joints in the sample attributed to that survey. The data may be recorded in a format similar to Table 7.

Table 7. Recording of Extent for Joint Spalling by Severity Level.

Severity Level	Spall Width (mm)	Extent (# of Slabs)
Level 1	> 30 to 75 mm	
Level 2	> 75 mm	

4.3.2 Data Recording for "D" Cracking – For each level of severity record the number of joints in the sample attributed to that severity. The data may be recorded in a format similar to Table 8.

Table 8. Recording of Extent for "D" Cracking by Severity Level.

Severity Level	Description of "D" Cracking	Extent # of joints)
Level 1	"D" cracks which are tight with no loose pieces or patches	
Level 2	"D" cracks with loose pieces or missing pieces that have been displaced or patched.	

4.4 The minimum data recorded shall contain the following:

a) Section Identification – For each data collection section the agency should list all information necessary to locate the section using its current referencing system.
b) Date of data collection. (Month\Day\Year)
c) Length of data collection section. (m to closest dm)
d) Average joint spacing (m to closest dm)
e) Number of shattered slabs within the sample (#)
f) Number of slabs with transverse cracking within the sample for each severity level. (#)
g) Number of slabs with longitudinal cracks within the sample for each severity level. (#)
h) Number of slabs with corner breaks within the sample for each severity level. (#)
i) Number of slabs with surface deteriorated within the sample for each severity level. (#)
j) Number of slabs with asphalt patches within the sample for each severity level. (#)
k) Number of joints with spalling within the sample for each severity level. (#)
l) Number of joints with "D" cracking within the sample for each severity level. (#)
m) Sample location (optional) – the beginning location of the sample.
n) Sample length (m).
o) Number of slabs within the section.

5. Quality Assurance

5.1 *Quality Assurance Plan* – Each agency shall develop an adequate quality assurance plan. Quality assurance includes survey personnel certification training, accuracy of equipment, daily control procedures, and periodic and on-going control activities. The following guidelines are suggested for developing such a plan.

5.2 *Training* – Certification training is the training or certification of personnel for proficiency in pavement rating or in operating equipment that must be used as part of quality assurance. Agencies are individually responsible for training and certifying their survey personnel.

5.3 *Equipment* – The basic output of any used equipment should be checked or calibrated according to the equipment manufacturer's recommendations. The equipment must operate within the manufacturer's specifications. A regular maintenance and testing program should be established for the equipment in accordance with the manufacturers recommendations.

5.4 *Test Sections* – Test or calibration sections should be located with known cracking types and levels statistics. These sections should be surveyed on a weekly basis. Comparison of these surveys can provide information about the accuracy of surveys and give insight into which raters/operators need additional training. Test sections should be rotated or replaced on a regular basis in order to assure that raters/operators are not repeating known numbers from prior surveys. As an alternate to this procedure, up to 5% of the data may be surveyed again on a daily basis as a quality check.

5.5 *Quality Checks* – Additional quality checks can be made by comparing last year's cracking survey summaries with current surveys. At locations where large changes occur, the pavement manager may consider additional investigation of the data.

CRACKING PROTOCOL
FOR CONTINUOUSLY REINFORCED CONCRETE

1. Purpose

1.1 This protocol defines standard procedures for estimating and summarizing cracking on continuously reinforced concrete pavement (CRCP) surfaces. Standardization will help produce consistent estimates of cracking for network level pavement management. This protocol applies to the National Highway System; application to other highways, streets and roads is left to the user-agency.

2. Scope

2.1 This protocol describes methods for estimating and recording cracking distress on CRCP pavement surfaces. Three cracking distresses are identified: Transverse cracking, longitudinal cracking, and punchouts.

2.2 Procedures are defined for estimating cracking, but detailed specifications are not included for equipment or instruments to make the estimates. Any equipment which can estimate as specified, with the accuracy stipulated herein and which can be adequately calibrated, is acceptable for this protocol.

2.3 This protocol does not purport to address all of the safety issues, if any, associated with its use. It is the responsibility of the user of this protocol to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2.4 Either automated or manual data collection surveys are acceptable when implementing this protocol.

a) *Automated Surveys* – Use a vehicle traveling at near highway speeds and collect data on the entire length of roadway (100% sample).

b) *Manual Surveys* – View distresses from the side of the roadway and collect data on a minimum 3% sample of the lane surveyed.

3. Cracking Definition and Estimation

3.1 *General Guidelines* – Each agency should be designate the lane(s) and direction(s) of travel to be surveyed based on sound engineering principles and management needs within the agency. The following guidelines are recommended to provide long term uniformity:

a) Survey the outside lane.
b) For undivided highways, survey one direction.
c) For divided highways, survey the outside lane in both directions.
d) For each survey cycle, use the same direction(s) of travel and survey lane(s).

3.2 *Cracking Definitions and Types* – A crack is a fissure or discontinuity in the pavement surface, not necessarily extending through the entire thickness of the pavement. This fissure develops after pavement construction. Three types of cracking distress are defined: transverse cracking, longitudinal cracking, and punchouts.

3.2.1 *Transverse Cracking Definition* – A transverse crack is any crack that crosses half the survey lane within 45 degree of perpendicular to the longitudinal centerline.

3.2.2 Longitudinal Cracking Definition – A longitudinal crack is a crack longer than two meters that is within 45 degree of parallel to the longitudinal center line.

3.2.3 *Punchouts Definition* – Punchouts are areas of distressed pavement separation from normal pavement by wide or spalled cracks. These areas will often exhibit spalling, breakup, and/or faulting. The most common form of punchout occurs between two or more closely spaced (usually less than 1.0 m) transverse cracks with short connecting longitudinal crack(s). A punchout may also be formed by intersecting transverse cracks (“Y” cracks) that have spalling and show signs of breakup failure.

3.3 *Rating Cracking Distress* – Cracks are surveyed in the selected travel line.

3.3.1 Rating Transverse Cracks and Severity Levels

a) Identify each transverse crack that crosses half the survey lane.

b) Identify intersecting transverse cracks (“Y” cracks) as one crack if the intersection occurs in the outside half of the survey lane. Identify as two cracks if both legs of the “Y” cross the outside half of the lane.

c) Identify spalled cracks. A crack is considered to be spalled if 10% or more of its length is spalled to a width of 30 mm or greater. (See Figure 1)

d) Estimate the mean crack width in millimeters.

3.3.1.1 Severity Level 1 – Cracks < 6 mm in width with no spalling.

3.3.1.2 Severity Level 2 – Cracks ≥ 6 mm in width with no spalling.

3.3.1.3 Severity Level 3 - Any transverse crack with spalling.

3.3.2 Rating Longitudinal Cracks and Severity Levels

a) Identify longitudinal cracks longer than two meters.

i. Estimate crack length in meters to the nearest decimeter.

ii. Estimate the mean crack width in millimeters.

b) Identify spalling cracks. A crack is considered to be spalled if 10% or more of its length is spalled to a width of 30 mm or greater.

3.3.2.1 Severity Level 1 – Cracks < 6 mm in width with no spalling

3.3.2.2 Severity Level 2 – Cracks ≥ 6 mm in width with no spalling.

3.3.2.3 Severity Level 3 – Any longitudinal crack with no spalling.

3.3.3 Rating Punchouts and Severity Levels (See Figure 2)

a) Identify each punchout. A punchout is identified by the spalling on the enclosed cracking or mean crack width. Spalling is estimated for the worst 10% of the crack. (See Figure 3).

b) Estimate mean crack width in millimeters.

c) Estimate the spalling width in millimeters for worst 10% or cracks.

d) Identify faulting or punchout.

e) Identify breakup of punchout.

3.3.3.1 Levels of Severity I – Punchout area defined by:

i. Cracks with widths < 3 mm and cracks spalled up to 75 mm wide (3 in.)

ii. “Y” cracks not included in this level.

3.3.3.2 Level of Severity – Punchout area defined by:

i. Spalling width > 75 mm and < 150 mm or

ii. Crack width > 3 mm and < 6 mm and

iii. Punchout area with no faulting or breakup.

iv. Includes “Y” cracks

3.3.3.3 Level of Severity 3 – Punchout area defined by:

i. Spalling width ≥ 150 mm or

ii. Crack width > 6 mm or

iii. Concrete within the punchout area is shattered or is loose and moves under traffic.

iv. Or punchout area is settled or faulted.

v. Includes “Y” cracks

Figure 1. Illustration of spalling at longitudinal and transverse cracking.

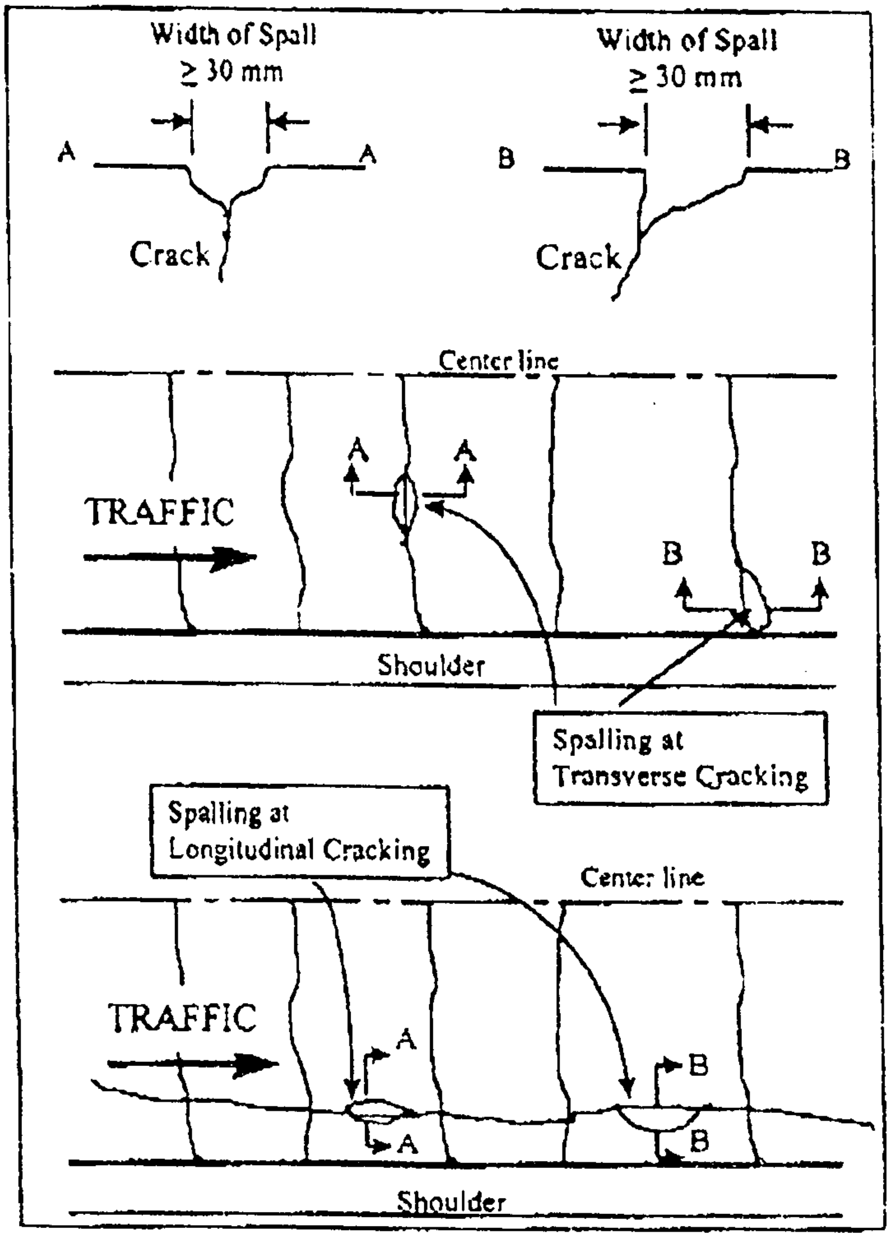


Figure 2. Illustration of Punchouts.

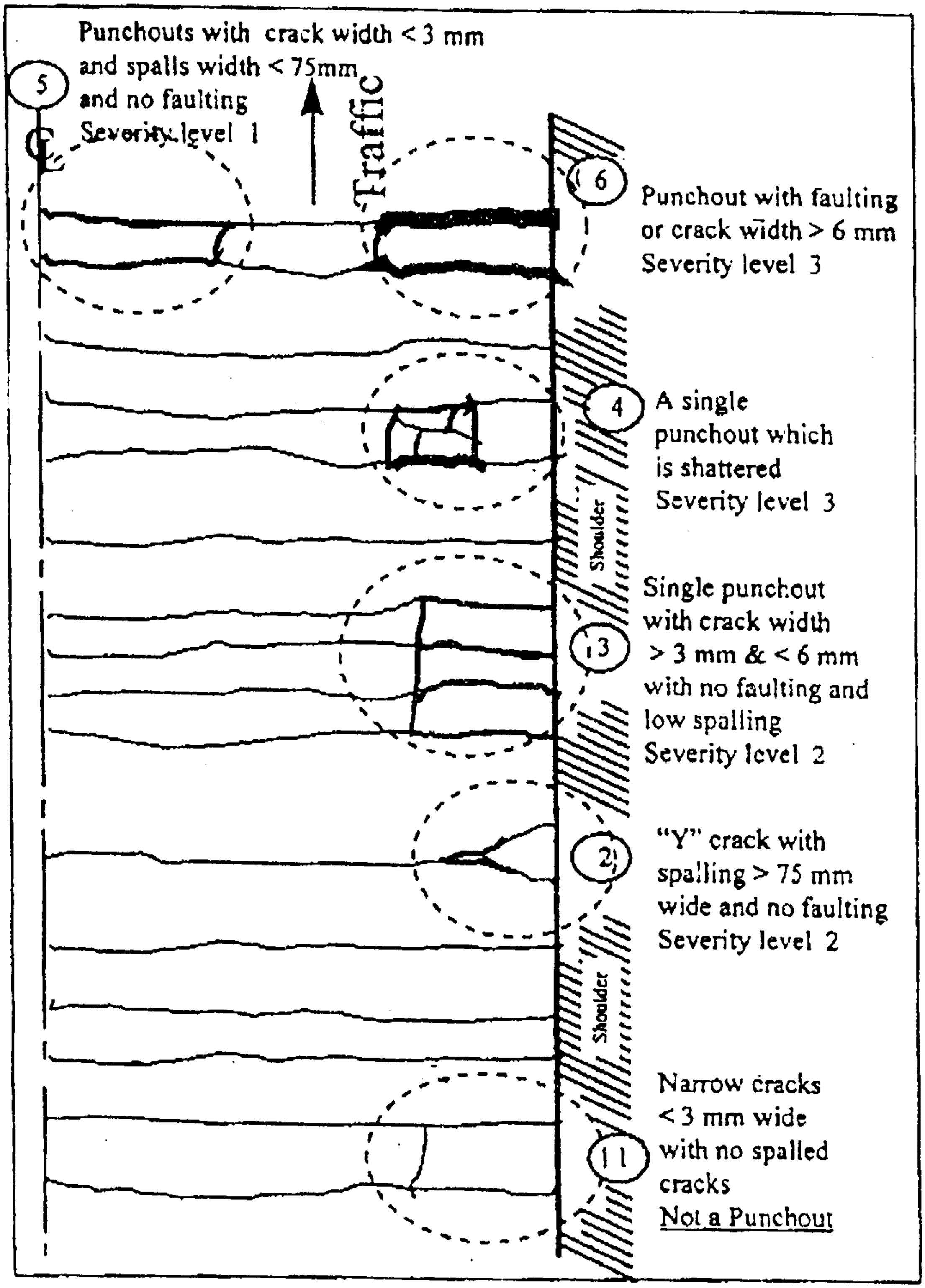
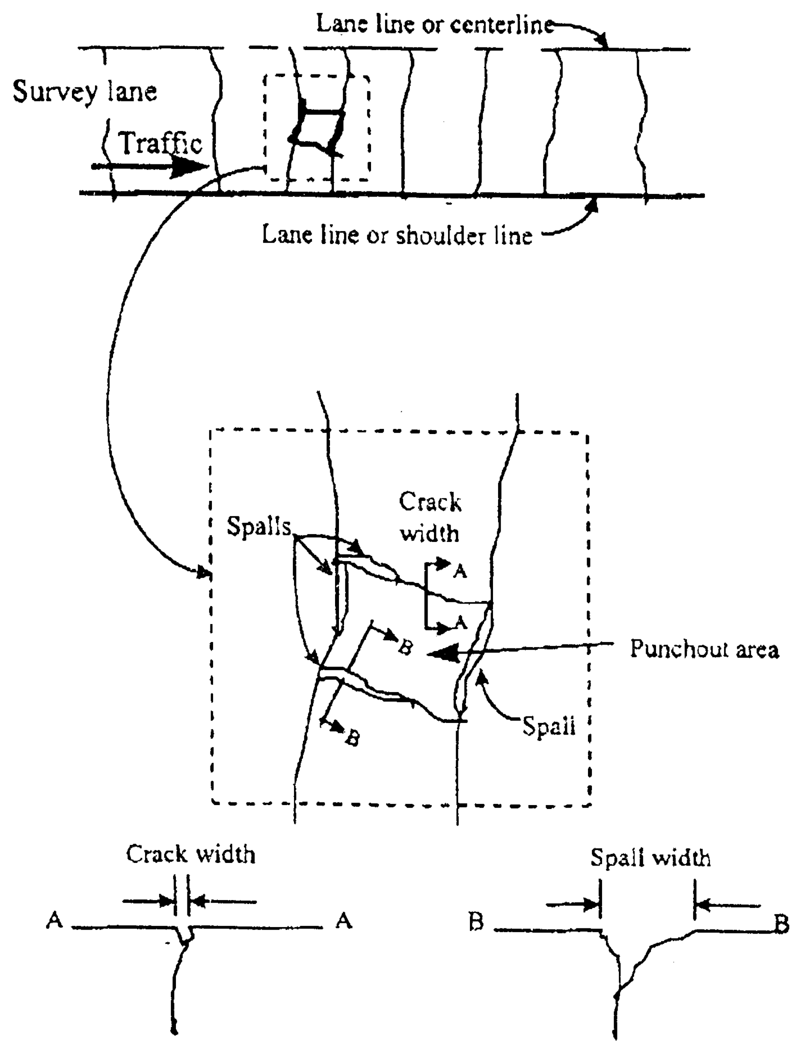


Figure 3. Illustration of punchout with spalling.



3.4 Data Collection Sections – The exact length of the data collection section is determined by the agency and shall be between 0.10 km and 1.0 km.

a) Automated Surveys – The entire length of the data collection section shall be surveyed (100% sample).

b) Manual Surveys – One 30 m long sample shall be surveyed per data collection section for transverse and longitudinal cracking. Punchouts will be surveyed throughout the entire data collection section. It should be noted that the 30 m sample represents 3% of a 1.0 km section length. To increase sampling percentage, an agency can use a shorter data collection section length.

Data for transverse cracking, longitudinal cracking, and punchouts shall be recorded as shown in the following sections. The item "sample" will be used as it applies to both automated methods and manual surveys. For automated surveys, the sample is collected on the entire length of the data collection section.

4.1.1. Data Recording for Transverse Cracking – For each severity level, record the number of transverse cracks in the sample. The data may be recorded in a format similar to Table 1.

Table 1. Recording of Extent for Transverse Cracking by Severity Level.

Level	**Condition and Crack Width**	**Extent (# of Cracks)**
Level 1	< 6 mm – not spalled	
Level 2	$\geq$ 6 mm – not spalled	
Level 3	Any spalled crack	

4.1.2. Data Recording for Longitudinal Cracking – For each severity level, record the length of longitudinal cracks attributed to the severity. The data may be recorded in a format similar to Table 2.

Table 2. Recording of Extent for Longitudinal Cracking by Severity Level.

Level	**Condition and Crack Width**	**Extent (length of Cracks, m)**
Level 1	< 6 mm – not spalled	
Level 2	$\geq$ 6 mm – not spalled	
Level 3	Any spalled crack	

4..1.3. Data Recording for Punchouts – The severity level of punchouts is determined using the description given in Table 3. The extend is recorded as the number of punchouts within each severity level for the entire data collection section. The data may be recorded in a format similar to Table 3.

Table 3. Recording of Extent for Punchouts by Severity Level.

Severity Level	**Description**	**Extent (# of Punchouts)**
Level 1	Bounded by cracks (with width < 3 mm and some spalling < 75 mm wide (3 in), but does not include "Y" cracks.	
Level 2	Spalling width $\geq$ 75 mm (3 in.) but < 150 mm (6 in.), or crack width $\geq$ 3 mm and < 6 mm. (Includes "Y" cracks).	
Level 3	Spalling width $\geq$ 150 mm (6 in.) or concrete in the punchout is shattered, or crack width $\geq$ 6 mm. (Includes "Y" cracks).	

3.5 The minimum data recorded shall contain the following:

a) Section Identification – For each data collection section the agency should list all information necessary to locate the section using its current referencing system.
b) Length of data collection section. (m)
c) Number of transverse cracks within the sample for each severity level. (#)
d) Length of longitudinal cracks within the sample for each severity level. (m)
e) Number of punchouts within the entire data collection section for each severity level. (#)
f) The date of collection (Month\Day\Year)
g) Sample location (optional) – The beginning location of the sample.
h) Sample length. (m)

4. Quality Assurance

4.1 *Quality Assurance Plan* – Each agency shall develop an adequate quality assurance plan. Quality assurance includes survey personnel certification training, accuracy of equipment, daily quality control procedures, and periodic and on-going control activities. The following guidelines are suggested for developing such a plan.

4.2 *Training* – Certification Training is the training or certification of personnel for proficiency in pavement rating or in operating equipment that must be used as part of quality assurance. Agencies are individually responsible for training and certifying their survey personnel.

4.3 *Equipment* – The basic output of any used equipment should be checked or calibrated according to the equipment manufacturer's recommendations. The equipment must operate within the manufacturer's specifications. A regular maintenance and testing program should be established for the equipment in accordance with the manufacturer's recommendations.

4.4 *Test Sections* – Test or calibration sections should be located with known cracking types and levels of statistics. These sections should be surveyed on a weekly basis. Comparison of these surveys can provide information about the accuracy of surveys and give insight into which raters/operators need additional training. Test sections should be rotated or replaced on a regular basis in order to assure that raters/operators are not repeating known numbers from prior surveys. As an alternate to this procedure, up to 5% of the data by surveyed again on a daily basis as a quality check.

4.5 *Quality Checks* – Additional quality checks can be made by comparing last year's cracking survey summaries with current surveys. At locations where large changes occur, the pavement manager may consider additional investigation of the data.

FAULTING PROTOCOL

1. Purpose

1.1 This protocol defines standard procedures for estimating and summarizing faulting on concrete pavement surfaces. Its purpose is to produce consistent estimates of faulting for network level pavement management. The intention is to measure faulting with a vehicle traveling in the designated lane at highway speeds. This protocol should be used on the National Highway System; its applicability to other highways, streets and roads is left to the user-agency.

2. Scope

2.1 This protocol describes a method for estimating faulting on concrete pavement surfaces. A fault is the difference in pavement surfaces elevation across a transverse joint.

2.2 Procedures are defined to measure faulting, but detailed specifications are not included for equipment or instruments to make the measurements. Any equipment that can measure as specified, with the accuracy stipulated herein and which can be adequately calibrated, is considered acceptable for this protocol.

2.3 This protocol does not purport to address all of the safety issues, if any, associated with its use. It is the responsibility of the user of this protocol to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

3. Fault Measurement

3.1 *General Guidelines* – Each agency should designate the lane(s) and direction(s) of travel to be surveyed based on sound engineering principles and pavement management needs within the agency. The following guidelines are recommended to provide long-term uniformity:

- 3.1.1. Survey the outside lane.
- 3.1.2. For undivided highways, survey one direction.
- 3.1.3. For undivided highways, survey the outside lane in both directions.
- 3.1.4. For each survey cycle, use the same direction(s) of travel and survey lane(s).

3.2 Faulting is defined as the difference in elevation across a transverse joint as shown in Figure 1.

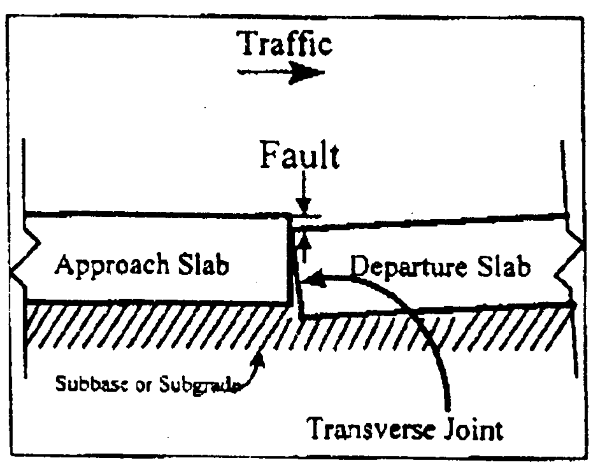
3.3 Faulting is calculated to the nearest millimeter by the following formula:

$$\mathbf{F = | D_1 - D_2 |}$$

Where: F = Faulting is the absolute value of the measured difference. (mm)

D_1, D_2 = Heights measured on either side of a transverse joint in the outside wheel path (mm).

Figure 1. View of Longitudinal Section of Faulting at a Transverse Joint.



4. Recording of Data

4.1 Data collection sections used by an agency shall be of constant length. The exact length of the data collection section is determined by the agency and shall be between 0.10 kilometer (km) and 1.0 km. Automated measurements of faulting are made across all transverse joints in the outside wheel path. Manual measurements (when used) are made across transverse joints 0.75 meters from the outside shoulder joint. For manual measurements, the sampling rate shall include at least 10% of all transverse joints. Faulting data shall be summarized for each data collection section into the four levels shown in Table 1.

4.2 All joints in the sample are counted and classified by severity level as shown in Table 1. The percentage of the joints at each severity level is calculated by dividing the number of joints in the sample within that level by the total number of joints measured in the section and multiplying by 100. These percentages shall be reported to the nearest percent for levels 2,3, and 4. The percentage for level 1 is calculated as 100 minus the sum of the percentages for levels 2,3, and 4.

Table 1. Faulting Data for Data Collection Section

Severity Level of Faulting	**Range of Faulting Estimates (mm)**	**Number of Joints at Level Shown**	**Percentage of Joints at Level Shown**
Level 1	< 6 mm	--	--
Level 2	≥ 6 mm and < 12 mm	--	--
Level 3	> 12 mm and < 25 mm	--	--
Level 4	≥ 25 mm	--	--

4.3 The minimum data recorded shall contain the following:

4.3.1. *Section Identification* – The agency should list all information necessary to locate the section using its current referencing system.

4.3.2. Length of the data collection section. (m)

4.3.3. Percentage of the section length for the four severity levels of faulting. (%)

4.3.4. The date of collection. (mm\dd\yyyy)

4.3.5. The average joint spacing in the section. (m)

5. Quality Assurance

5.1 *Quality Assurance Plan* – Each agency shall develop a quality assurance plan. Quality assurance includes survey personnel certification training, accuracy of equipment, daily quality control procedures, and periodic and on-going quality control. The following guidelines are suggested for developing such a plan.

5.2 *Training* – Certification Training is the training and certification of personnel for proficiency in using the measuring equipment according to this protocol and other applicable agency procedures. Agencies are individually responsible for training and certifying their data collection personnel.

5.3 *Test Sections* – Calibration test sections should be selected with pre-measured faults. These sections should be measured by the team on a weekly basis. Evaluations of these measurements can provide information about the accuracy and give insight into which raters need additional training. New test sections should be selected on a regular basis in order to assure that the operators are not repeating known values during the test. An alternate to test sections would be to re-measure up to 5% of the data as a daily or weekly quality check.

5.4 *Quality Checks* – Additional quality checks can be made by comparing last year's faulting statistics with current measurements. At locations where large changes occur, the pavement manager should require additional investigation of the data. A regular maintenance and testing program should be established for the fault measuring equipment in accordance with manufacturers' recommendations.

6. Reference Documents

[SHRP 93]	"Distress-Identification Manual for the Long-Term Pavement Performance Project," Strategic Highway Research Program, SHRP-P-338, Washington, D.C., 1993.
[ASTM 95]	"Standard Practice for Use of Terms Precision and Bias in ASTM Test Methods," ASTM Designation: E177-90a.
[AASHTO 93]	"AASHTO Guide for Design of Pavement Structures, 1993," American Association of State Highway and Transportation Officials (AASHTO), 1993.

RUT DEPTH PROTOCOL

1. Purpose

1.1 This protocol defines standard procedures for estimating and summarizing rut depth on asphalt pavement surfaces. Its purpose is to produce consistent estimations of rut depth for network level pavement management. The intention is to measure rut depth in a vehicle traveling in the designated lane at highway speeds. This protocol should be used on the National Highway System; its applicability to other highways, streets and roads is left to the user-agency.

2. Scope

2.1 This protocol describes a three-point method for estimating rut depth on asphalt pavement surfaces. Three equally spaced vertical measurements are taken from the pavement surface to a horizontal reference line, one on each wheel path and one taken midway between the wheel paths. Based on the differences in these measurements, rut depth is estimated.

2.2 Procedures are defined for measuring rut depth, but detailed specifications are not included for equipment or instruments making the measurements. Any equipment which can measure as specified, with the accuracy stipulated herein and which can be adequately calibrated, is acceptable for this protocol.

2.3 This protocol does not purport to address all of the safety issues, if any, associated with its use. It is the responsibility of the user of this protocol to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

3. Rut Measurement

3.1 *General Guidelines* – Each agency should designate the lane(s) and direction(s) of travel to be surveyed based on sound engineering principles and management needs within the agency. The following guidelines are recommended to provide long-term uniformity:

- 3.1.1. Survey the outside lane.
- 3.1.2. For undivided highways, survey one direction.
- 3.1.3. For divided highways, survey the outside lane in both directions.
- 3.1.4. For each survey cycle, use the same survey direction(s) of travel and survey lane(s).

3.2 A rut is a longitudinal surface depression in the wheel path(s) of a pavement surface.

3.3 Rut depths are estimated in both wheel paths of the survey lane. Measurements to estimate rut depth are made longitudinally at maximum intervals of 15 meters (50 feet) and rut depth is calculated by the following formula.